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THE VOYAGER FLIGHTS TO JUPITER AND SATURN

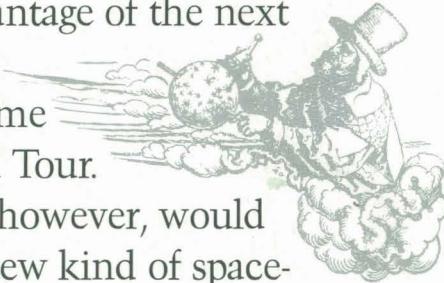


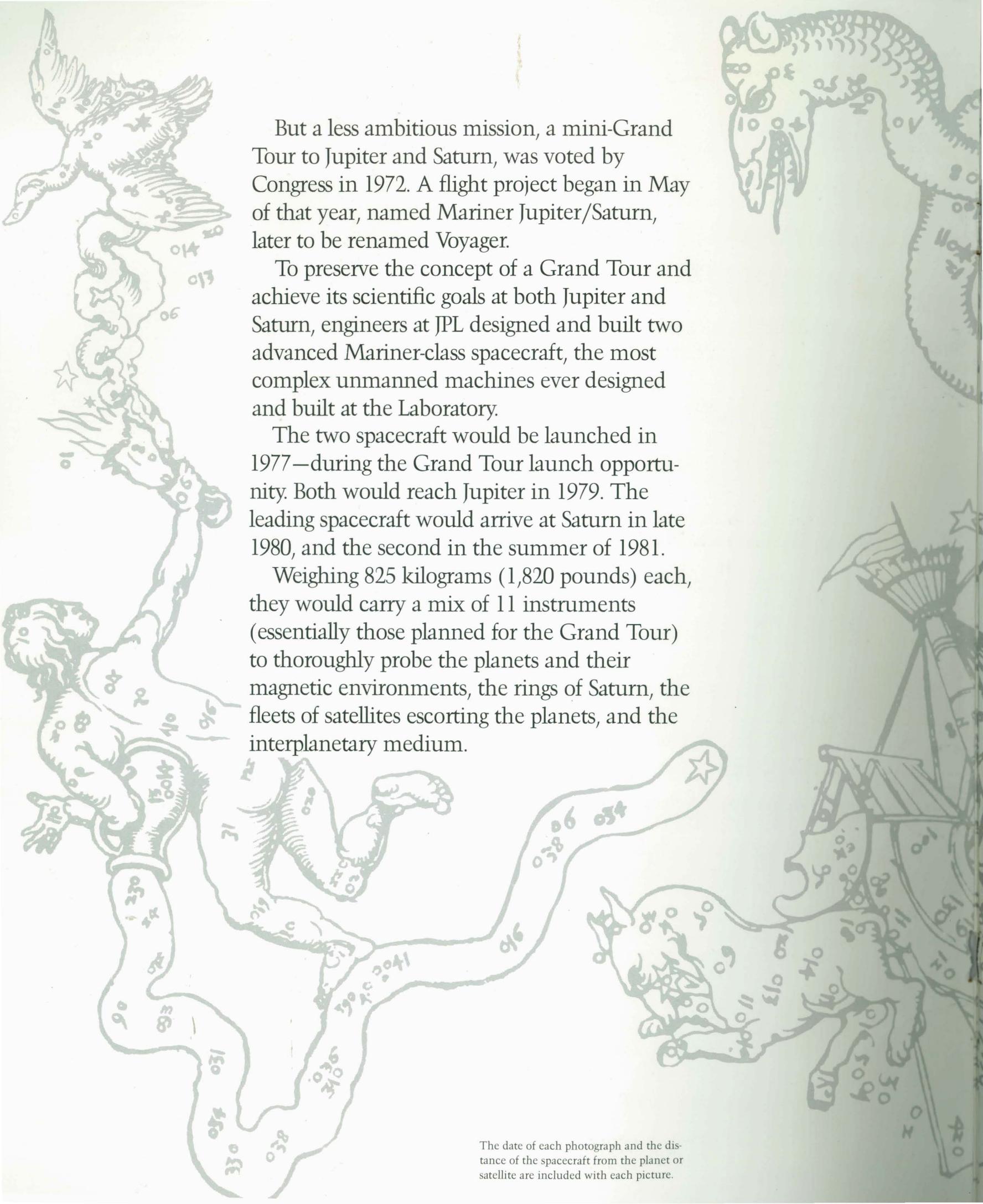
s the giant outer planets—Jupiter, Saturn, Uranus, and Neptune—perform their ancient, stately dance with the Sun, they whirl into a pattern each 175 years that allows a spacecraft launched from Earth to Jupiter to visit them all. Each planet's gravity bends the spacecraft's flight path toward the next and increases the velocity.

In the 1960s, engineers at NASA's Jet Propulsion Laboratory proposed a mission for 1977 that would take advantage of the next such opportunity.

The mission became known as the Grand Tour.

The Grand Tour, however, would require an entirely new kind of spacecraft, a design with capabilities far beyond the simpler machines that had reached the Moon, Venus, and Mars; it would have to survive the intense radiation at Jupiter and operate almost flawlessly for more than a decade. The new craft would need the decision-making capability to detect and react to a variety of internal problems, since command times from Earth, to provide a solution, would stretch to hours during the long flight. That long-life requirement alone was staggering—far longer than for any other space machine those engineers had designed.





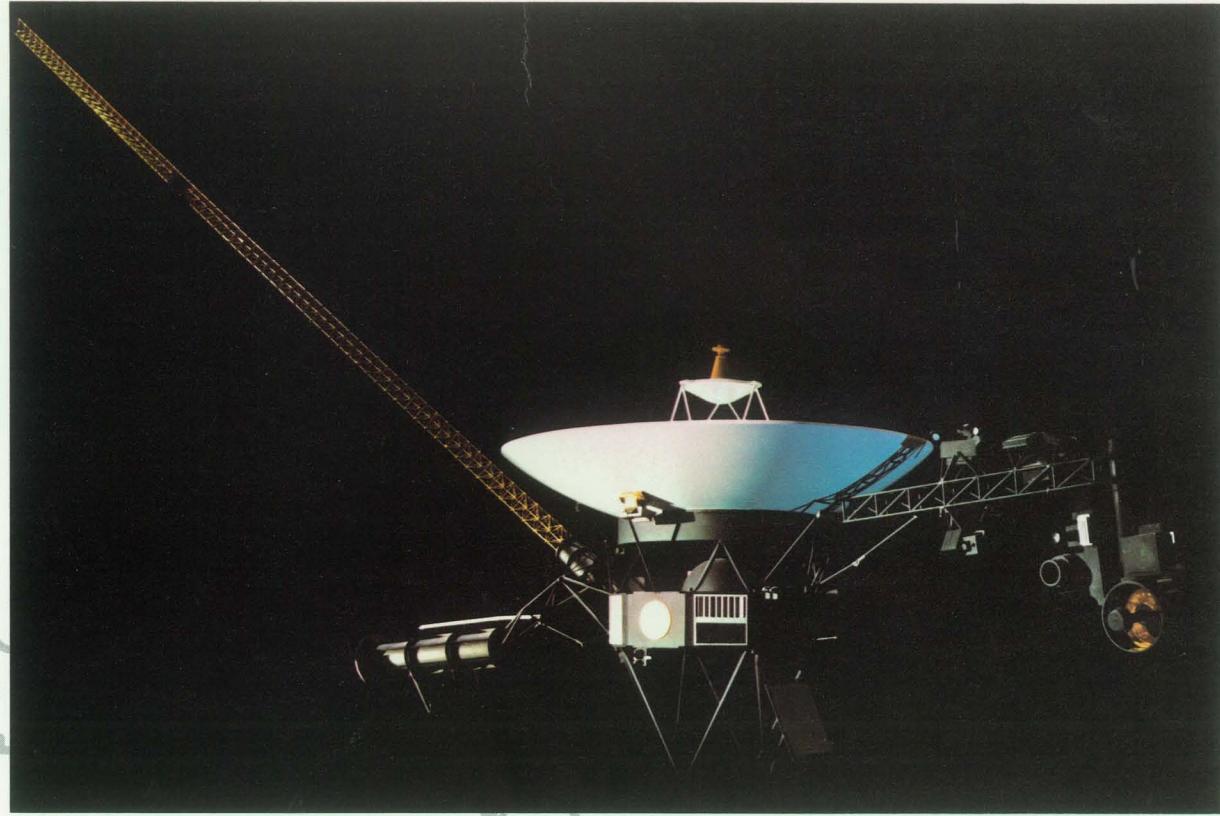
But a less ambitious mission, a mini-Grand Tour to Jupiter and Saturn, was voted by Congress in 1972. A flight project began in May of that year, named Mariner Jupiter/Saturn, later to be renamed Voyager.

To preserve the concept of a Grand Tour and achieve its scientific goals at both Jupiter and Saturn, engineers at JPL designed and built two advanced Mariner-class spacecraft, the most complex unmanned machines ever designed and built at the Laboratory.

The two spacecraft would be launched in 1977—during the Grand Tour launch opportunity. Both would reach Jupiter in 1979. The leading spacecraft would arrive at Saturn in late 1980, and the second in the summer of 1981.

Weighing 825 kilograms (1,820 pounds) each, they would carry a mix of 11 instruments (essentially those planned for the Grand Tour) to thoroughly probe the planets and their magnetic environments, the rings of Saturn, the fleets of satellites escorting the planets, and the interplanetary medium.

The date of each photograph and the distance of the spacecraft from the planet or satellite are included with each picture.

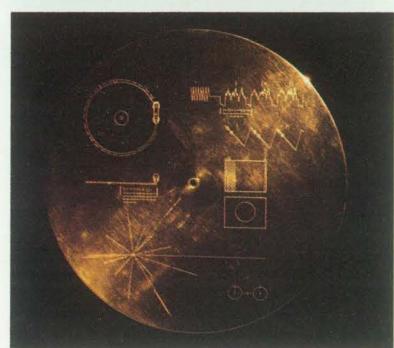


Two identical Voyager spacecraft have completed their initial investigations of Jupiter and Saturn.

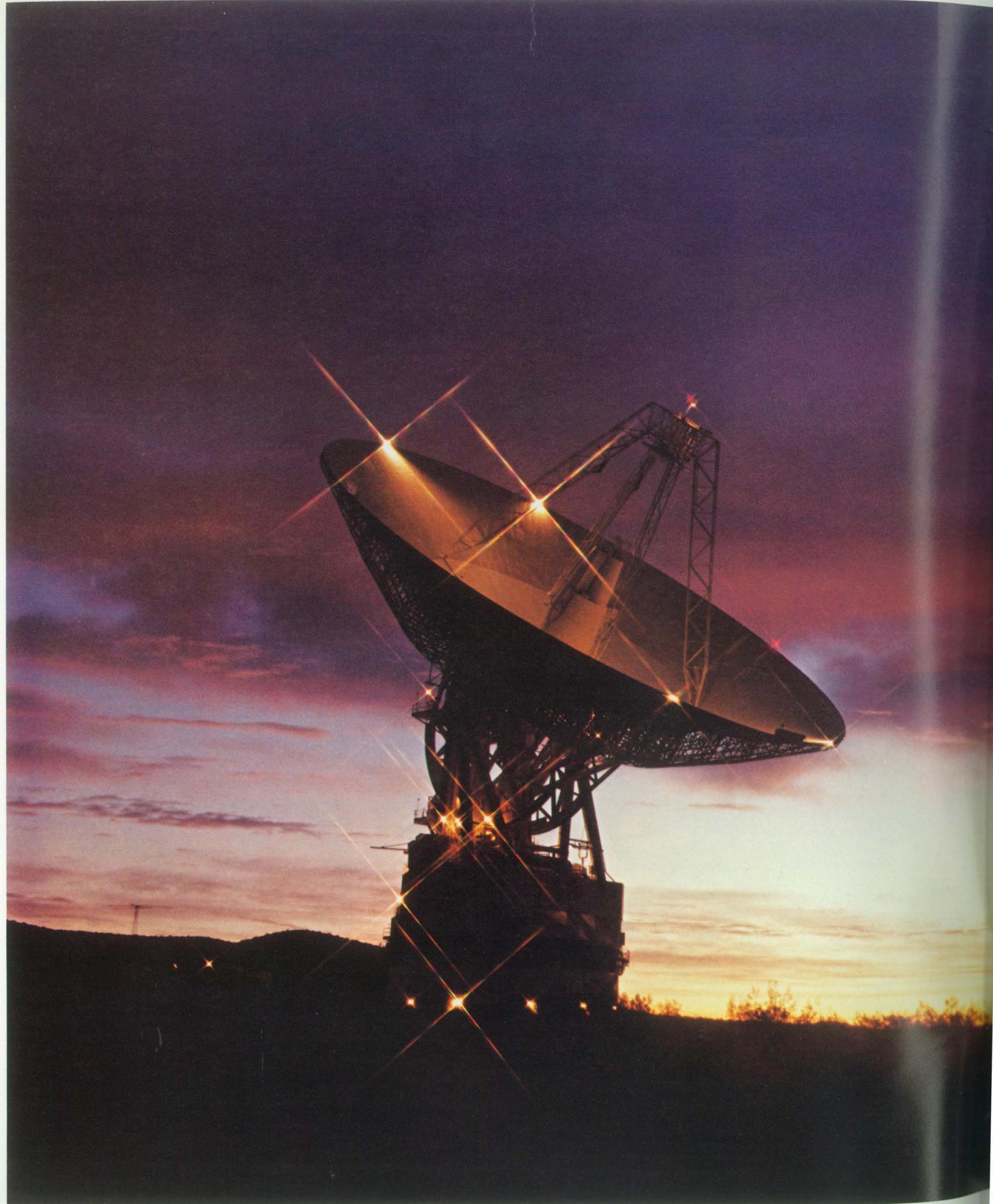
*"Their ships are swift as a bird
or a thought."*

HOMER

Each Voyager carries a record containing sounds and pictures of Earth: messages to any who might find them.



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FOREWORD

Voyagers 1 and 2 are the distant eyes and ears of an outward-bound civilization.

The swiftest and most complex robotic extensions of human intelligence ever built, they have journeyed more than a billion miles into space since their launch in 1977. And by the end of the century they will have traversed billions of miles more to the edges of true interstellar space, the point where the void between the stars begins. That is when their job will end, because we will no longer be able to track them.

Voyager 1, having completed its planetary exploration tasks, is now sampling the ocean-like tides and currents of the solar wind and searching for the limits of our Sun's influence. Voyager 2 is on course to Uranus and to distant Neptune for close encounters in 1986 and 1989 respectively.

At long last, we are beginning to know other heavenly bodies as intimately as we know our Earth. And we are beginning to feel at home in the Universe.

Before Voyager 1 sent back the first close-up pictures of Jupiter's Galilean moons, scientists had been expecting views of four worlds preserved in cold storage for aeons. But we found, incredibly, that a half-billion miles from

Earth is a world called Io that is very much alive, a moon with active volcanoes. The other three moons, though less dramatic than Io, are individually fascinating and, together with Jupiter, form a system that parallels that of the Sun and the inner planets. And Jupiter itself is an astonishingly dynamic planet with violent storms and swirling eddies. We later saw the majestic rings of Saturn and that planet's many moons, and discovered that one—Titan—has a thick atmosphere containing hydrocarbon molecules and, probably, methane clouds and rain.

Such is the pace of our discoveries that we have rewritten the astronomy textbooks several times during the past decade.

This new wealth of information has enhanced our understanding of the Earth by giving us a vastly broader context in which to view our planet.

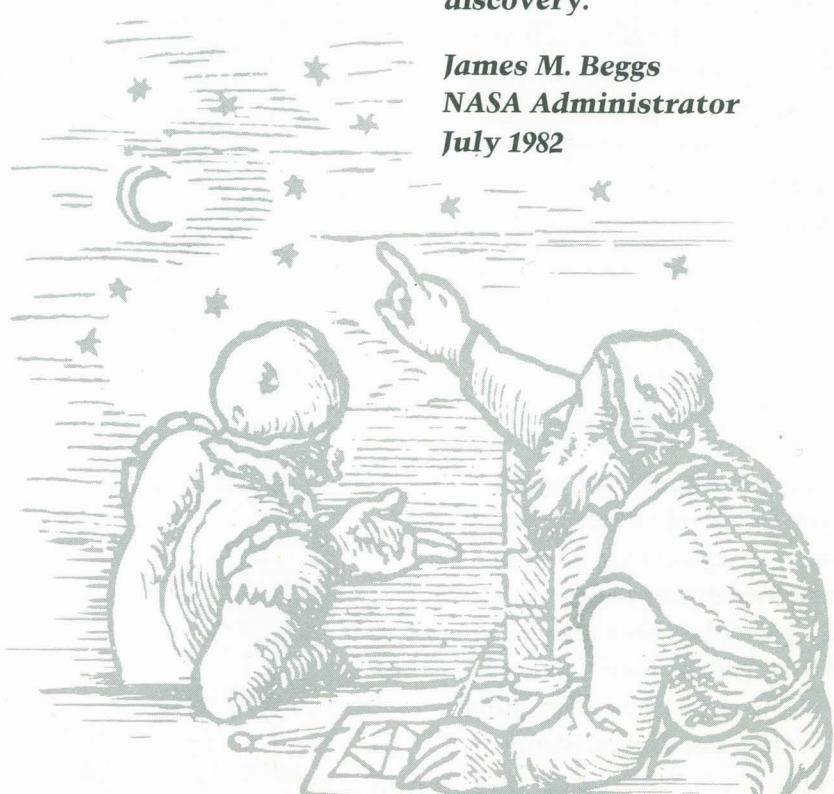
We no longer are only "riders on the Earth together," but inhabitants of a solar system whose other worlds we have seen and whose music we have heard.

The wondrous discoveries chronicled in this book are but a hint of those awaiting us. We will return to Jupiter with the Galileo spacecraft, this time to enter its atmosphere. We will map the unseen surface of Venus, and initiate the exploration of the comets and asteroids.

Even as we continue to explore the solar system, we will be charting new paths among the stars. The Infrared Astronomical Satellite, followed first by the Space Telescope and then the Gamma Ray Observatory, will be our new eyes and ears as we move from the neighborhood of the planets to that of the stars and galaxies.

We have truly only just begun our journey of discovery.

James M. Beggs
NASA Administrator
July 1982



Three huge antennas around the world track the Voyagers. This 64-meter (210-foot) giant is located in the California desert.

THE FLIGHTS TO JUPITER

August 20, 1977, was a steamy Florida day on the Titan-Centaur launch pad at Cape Canaveral Air Force Station. At 10:29 a.m., Voyager 2 lifted into the sky on the opening leg of its trip to the outer reaches of the solar system. (The first spacecraft launched was called Voyager 2, because the second Voyager to be launched would overtake it in flight and become Voyager 1.)

Within 10 hours, Voyager 2 passed the Moon. By November it had passed Mars' orbit. In early December Voyager 2 was sailing into the edge of the asteroid belt, a region of interplanetary reefs and shoals out beyond Mars.

Voyager 1 followed its twin from the Florida launch pad two weeks later, on September 5, 1977. It followed the same itinerary as Voyager 2, overtaking it just after entering the asteroid belt in mid-December.

A year after entering the asteroid belt, Voyager 1 was drawing near to Jupiter. Its cameras began sending photos to Earth at a range of 50 million kilometers (31 million miles) from Jupiter, pictures that soon surpassed the best taken through Earth-based telescopes. The resolution improved, until features only a few kilometers in diameter appeared. And scientists converged on JPL for the first encounter.

One hundred fifty scientists, members of the 11 science teams, were exultant. Not only would their instruments quickly provide a more detailed study of Jupiter than had been compiled during the centuries the planet had been observed, but they knew they stood personally on the brink of exciting scientific discoveries. Members of the photo team, for example,

knew that a color motion picture of Jupiter's turbulent clouds, to be made from several hundred still photos, would yield new information on the complex atmosphere of Jupiter.

Thus the new year of 1979 brought the first close-up, high-resolution viewing of Jupiter. Voyager 1 made its closest approach to Jupiter on March 5 and continued its exploration of the Jupiter system into early April. By the time the first encounter had ended, Voyager 1 had taken 16,500 photos, and our knowledge of Jupiter had changed as profoundly as it did 369 years before, when Galileo

Galilei first saw that Jupiter was circled by its own cluster of satellites.

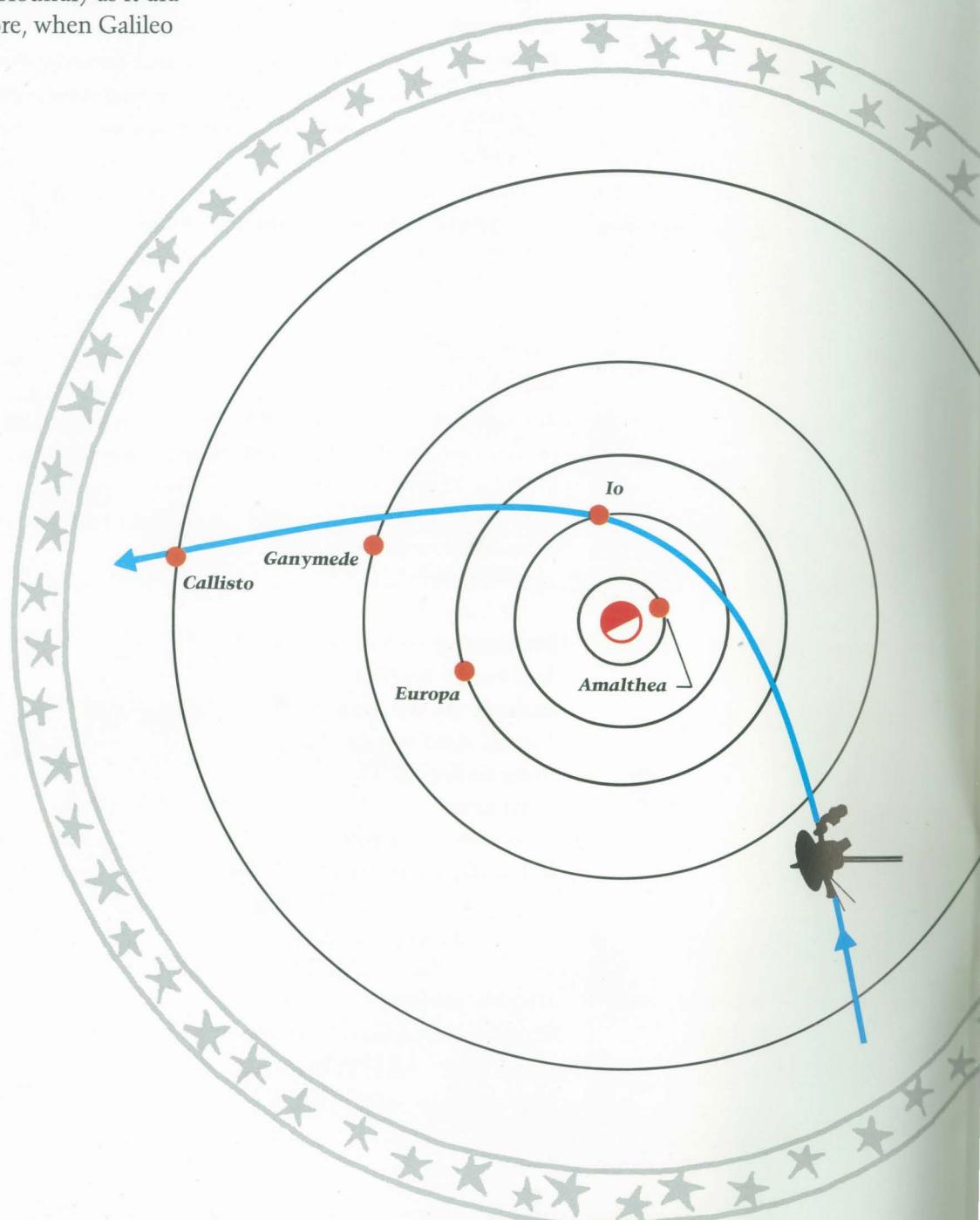
THE FIRST JUPITER ENCOUNTER

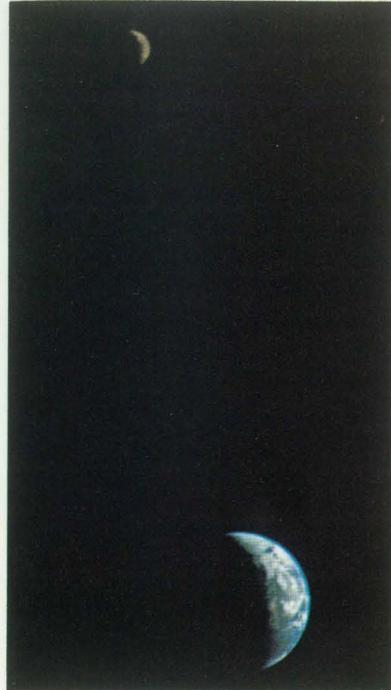
From the beginning of the first Jupiter encounter, scientists were stunned by the discoveries contained in the data. Each day, as the Voyagers poured millions of bits of data to Earth around the clock, science teams reported a bounty

of exciting new findings to the hundreds of reporters who jammed the Voyager news room at JPL.

Easily the most exciting was the discovery of the first extra-terrestrial volcanoes. At least eight or nine volcanoes on the reddish satellite Io had erupted before the spacecraft cameras. No one had ever seen an active volcano anywhere beyond Earth.

One photo of Io showed a plume-shaped object standing



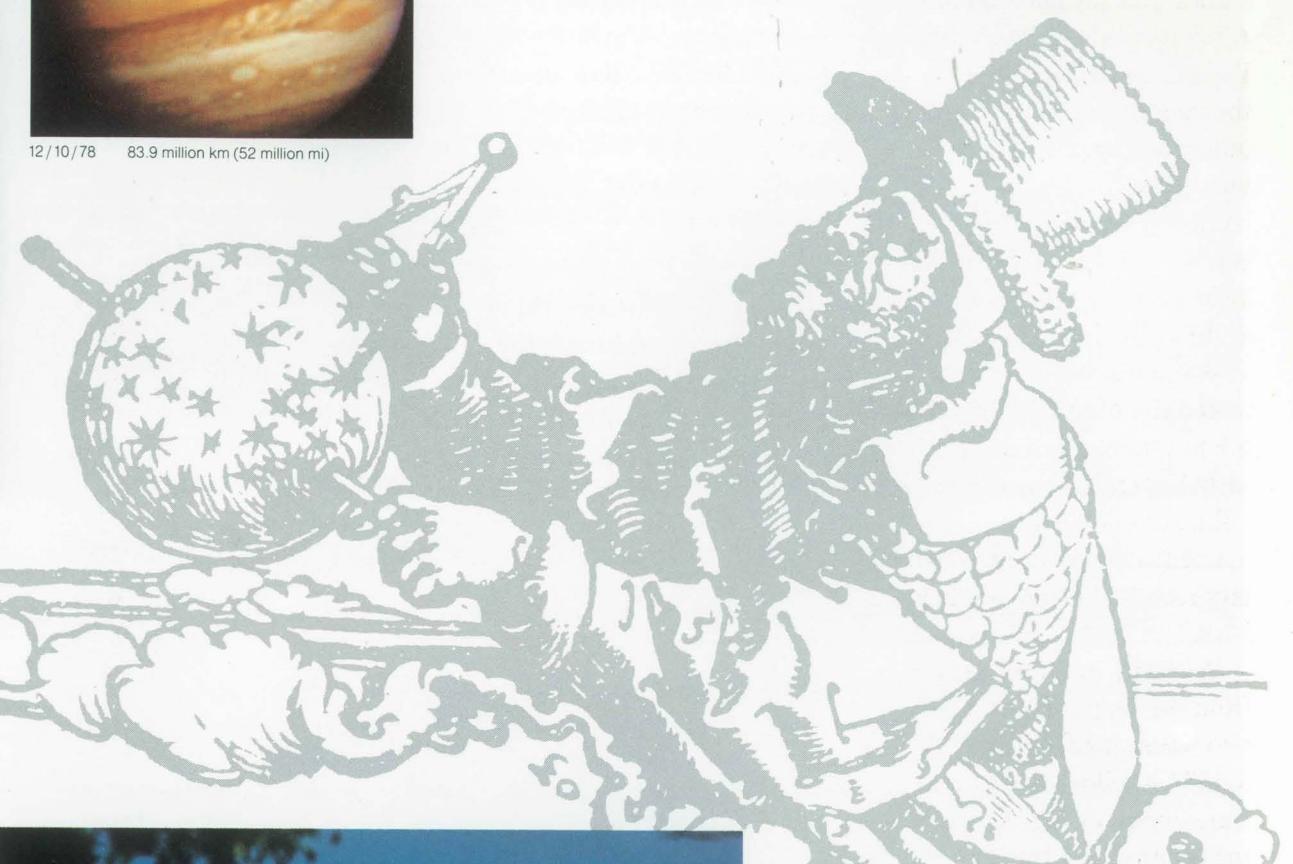


9/18/77 11.66 million km (7.25 million mi)



12/10/78 83.9 million km (52 million mi)

Voyager 1 took the first single-frame photo of Earth and Moon, and an early picture of huge, multicolored Jupiter.



A Voyager leaves Earth atop its flaming Titan-Centaur launch vehicle in the summer of 1977.

***"The heavens themselves,
the planets, and this
center, Observe degree,
priority, and place."***

SHAKESPEARE

off the satellite's limb. A large volcano was erupting material to an altitude of 250 kilometers (155 miles) above the Ionian surface. Once the first volcano was found, discovery of others followed quickly. One volcano earned the nickname "the tarantula," since it resembled a large spider standing above the surface on legs of ejecta.

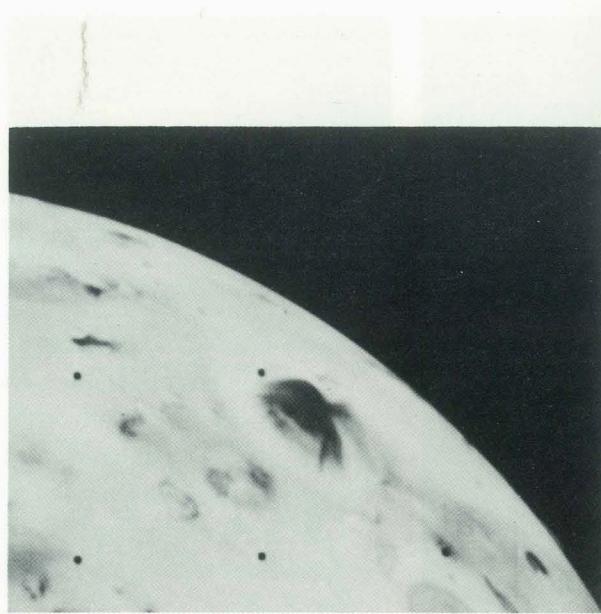
One scientist, a veteran of the study of other planets, called the discovery, "the most important, so far, in the planetary-exploration program."

In the motion picture of Jupiter mentioned earlier, scientists could see, for the first time, the activity in Jupiter's gigantic Great Red Spot. The feature had been observed from Earth for about 300 years, but never in such detail. The Great Red Spot is a counterclockwise-rotating storm system. Its outer edge makes a complete circuit once every six days, while at the center almost no motion can be seen.

And Jupiter had a ring, similar to those of Saturn and Uranus. While no one really expected to see a ring of dust or ice at Jupiter, a single opportunity to look for one had been thoughtfully programmed into Voyager 1's sequences. At the moment Voyager 1 dived across Jupiter's equatorial plane on its inbound leg, its cameras shuttered, and about 37 minutes later the image began to build up on the TV monitors at JPL. The ring around Jupiter was extremely faint, but it was there, a band of fine particles that had been undetectable from Earth.

The surfaces of all four Galilean satellites, seen in detail for the first time, proved to be a surprise. Io was covered with reddish sulfur from its volcanoes. Europa appeared laced

with long lines—perhaps either cracks or ridges—on its surface. Ganymede was peppered with craters, interspersed with grooves that wound their way over the surface like huge dune buggy tracks. The surface of Callisto was a jumble of thousands of craters of all sizes; Callisto was the most heavily bombarded satellite ever seen.

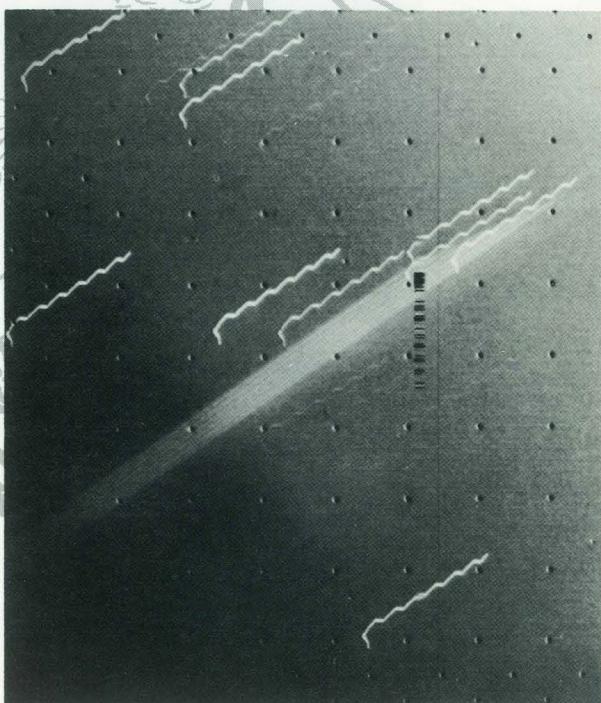


3/4/79 499,000 km (310,000 mi)

Red Io and white Europa orbit above Jupiter's multihued clouds. The Great Red Spot is the largest of many storms. ▷



Io's volcanoes and lava lakes cover the landscape and continually resurface it, so that any impact craters have disappeared.



33/1/78 12 million km (750 000 mi)

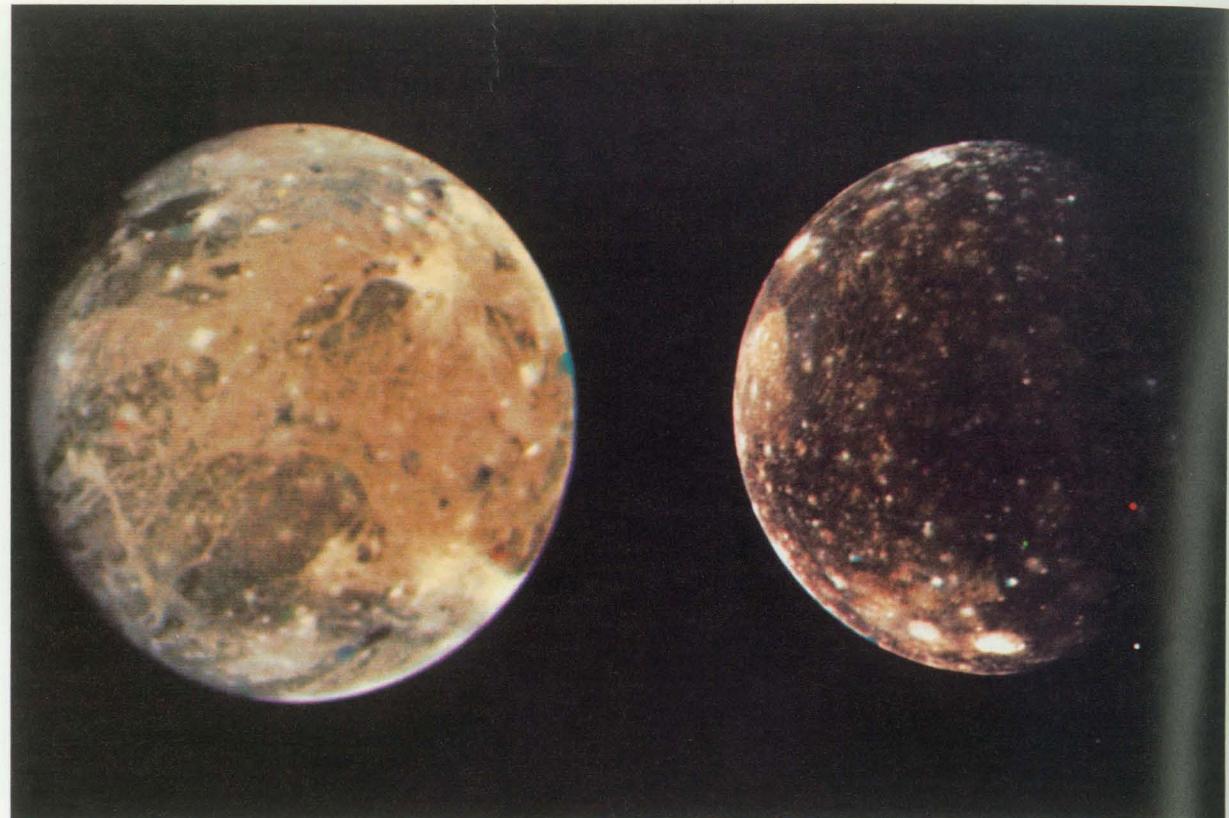
Jupiter's ring and the trails of distant stars appear in this ring-discovery photo by Voyager 1



been able to determine Jupiter's rotation rate from the radio noise that originated in the planet's magnetosphere.

They also had found that a strange, tube-like flow of electric current and energetic particles travels along an invisible magnetic pathway between Jupiter and Io. From Earth-based observations, scientists predicted that the tube might carry about 1 million amperes of current.

Voyager 1 was targeted to fly directly through the tube to make the first direct measurements of its strength. Although the spacecraft went exactly where it was targeted, the tube was not there. The flux tube had been skewed from the predicted position by physical forces. But the Voyager data were sufficient to reveal that the tube carried about three times the current anticipated—3 million amperes. Scientists hastened to add, however, that the voltage was so low that the current could not be detected by anyone standing on Io.

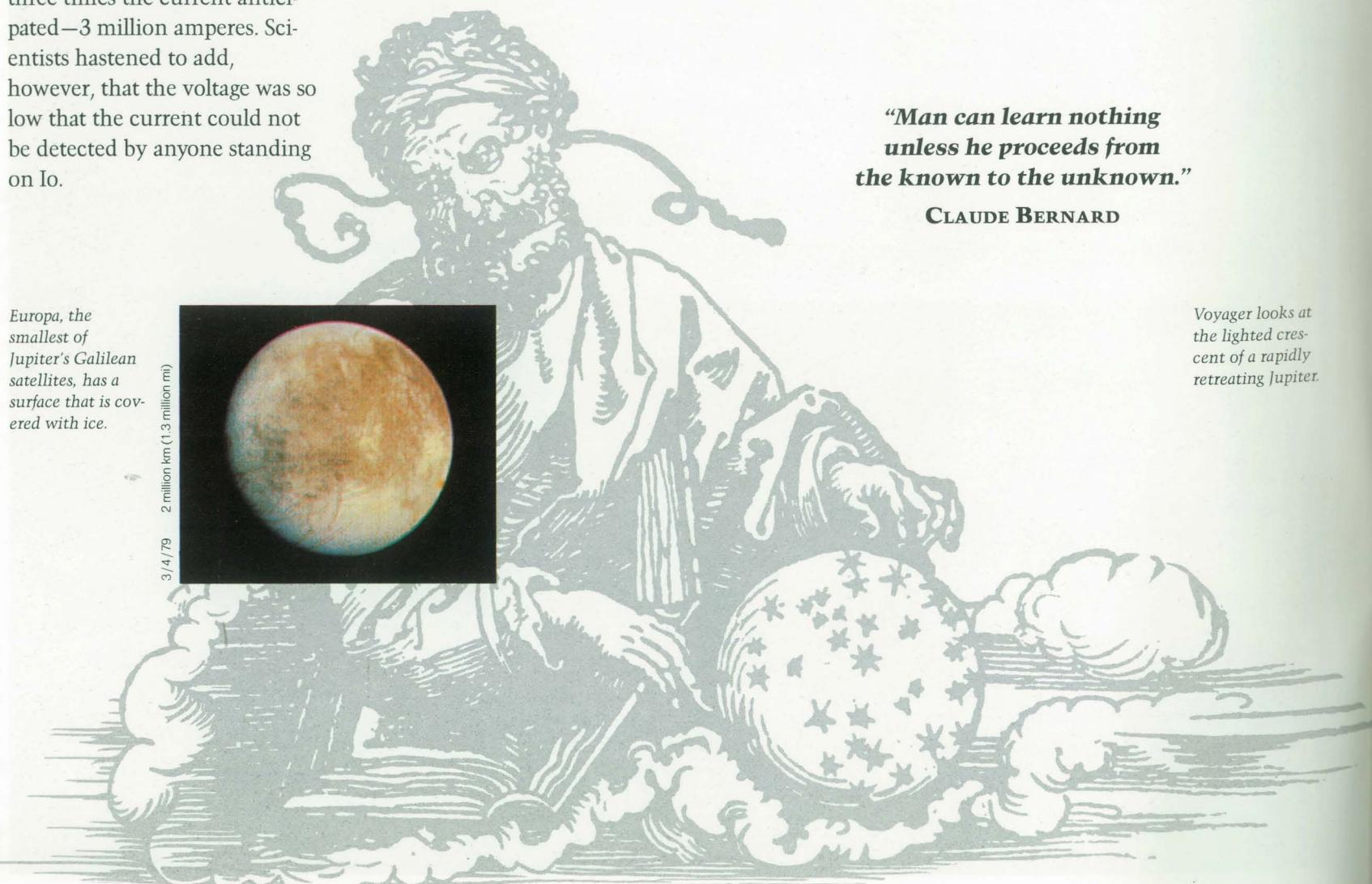


3/79 Ganymede: 3.4 million km (2 million mi)

Ganymede (left) and Callisto, Jupiter's largest satellites, of which Ganymede is the larger; Callisto's

surface is a record of ancient bombardment.

3/79 Callisto: 6.9 million km (4.3 million mi)



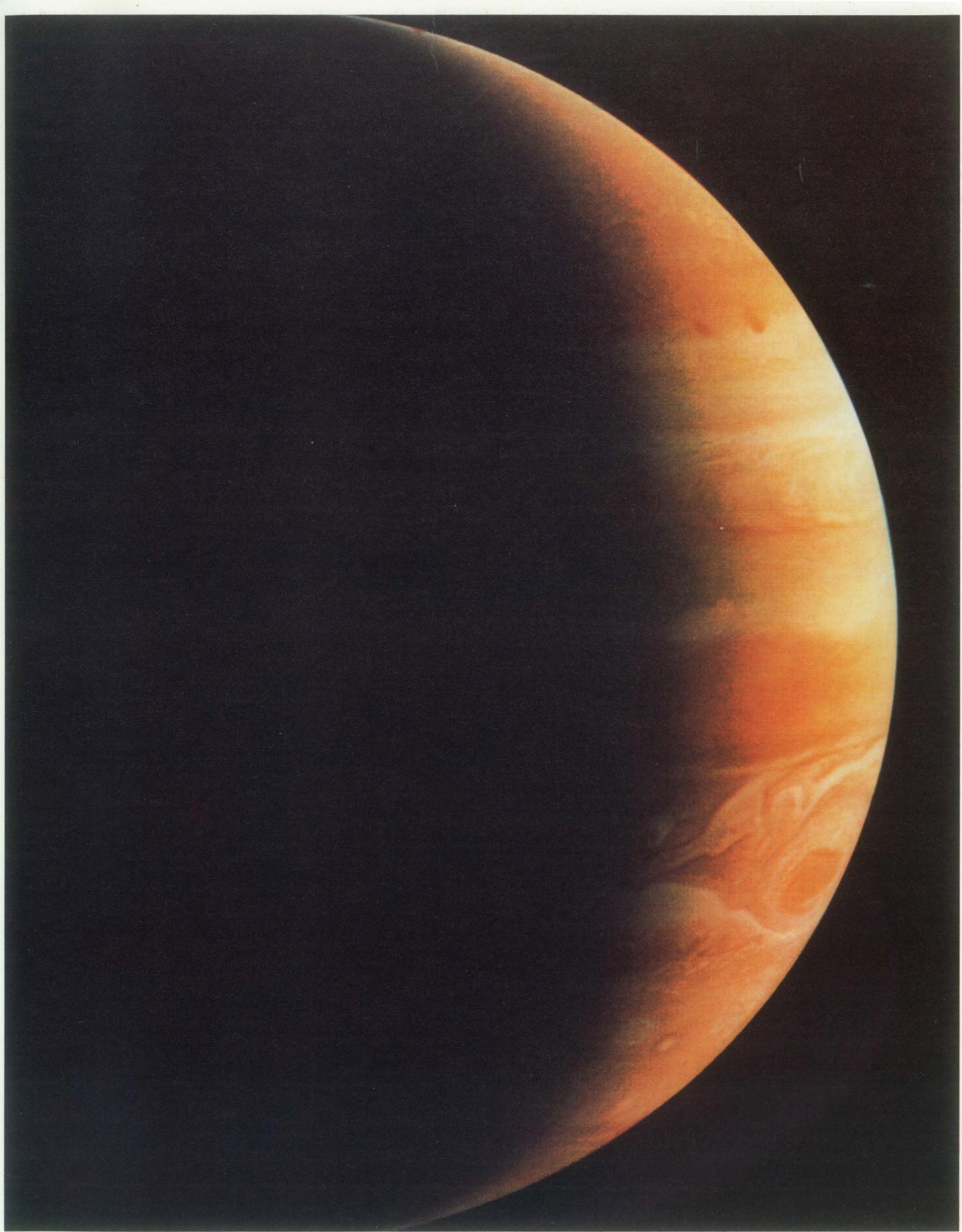
Europa, the smallest of Jupiter's Galilean satellites, has a surface that is covered with ice.

3/4/79 Europa: 2 million km (1.3 million mi)

"Man can learn nothing unless he proceeds from the known to the unknown."

CLAUDE BERNARD

Voyager looks at the lighted crescent of a rapidly retreating Jupiter.





VOYAGER 2 AT JUPITER

As Voyager 1's encounter drew to an end, scientists and engineers altered many of the mission instructions programmed into Voyager 2's computers, radioing target and timing changes to exploit the flood of new data from Voyager 1.

Voyager 2's encounter began in late April, two weeks after Voyager 1 turned from looking over its shoulder at the receding Jupiter and settled down for the long cruise to Saturn.

Voyager 2 made its closest approach to Jupiter on July 9, 1979, and the planet provided new data on its tumultuous weather. The swirling cloud patterns recorded by Voyager 1 had changed and continued to change as Voyager 2 approached. Those cracks or

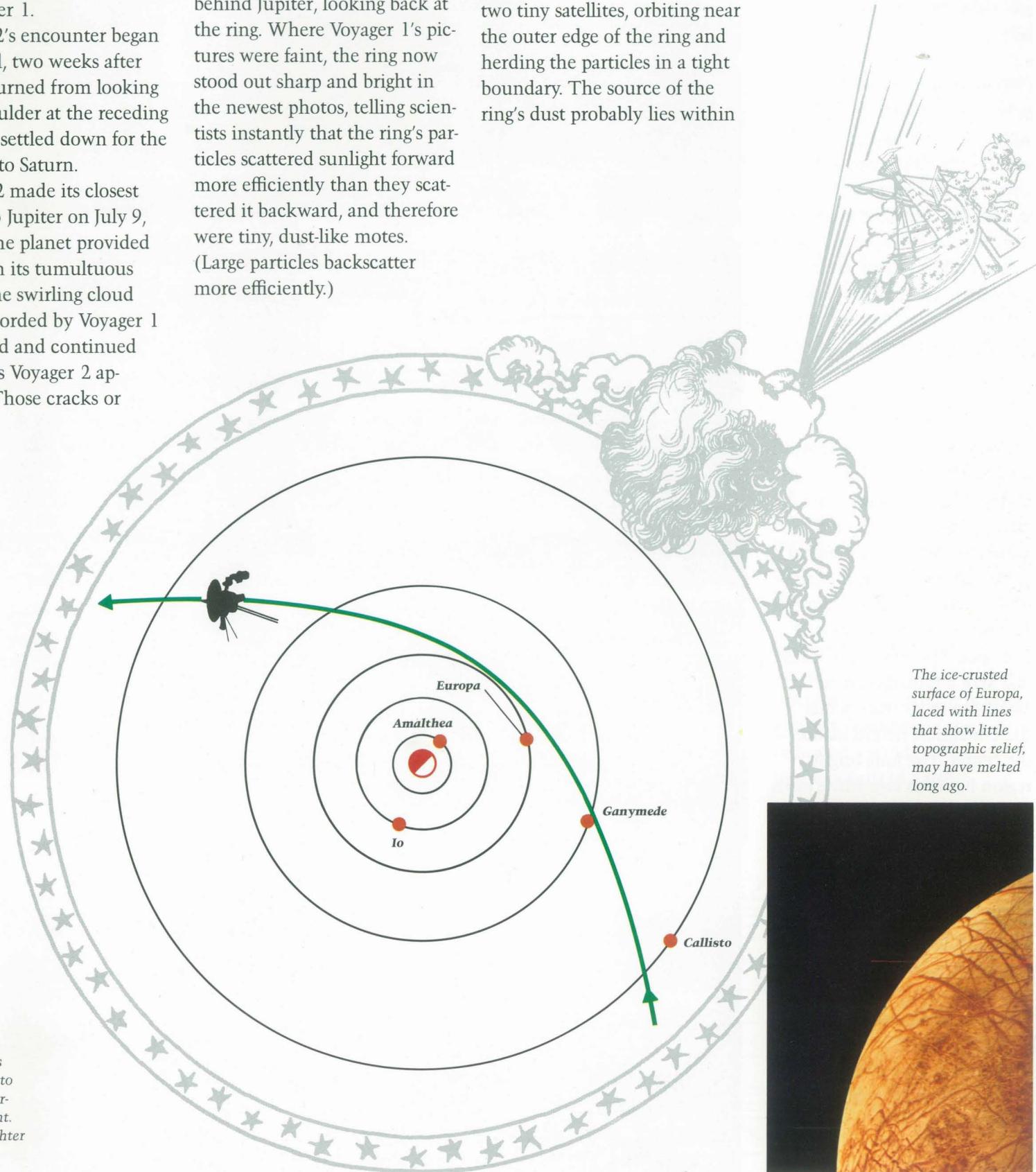
ridges on Europa, on closer scrutiny, were so flat, "They looked as if they had been painted on the satellite with a felt marker." And the largest of Io's volcanoes had stopped erupting.

Voyager 2 took pictures of Jupiter's ring on the inbound leg, but more interesting were the pictures it took while behind Jupiter, looking back at the ring. Where Voyager 1's pictures were faint, the ring now stood out sharp and bright in the newest photos, telling scientists instantly that the ring's particles scattered sunlight forward more efficiently than they scattered it backward, and therefore were tiny, dust-like motes. (Large particles backscatter more efficiently.)

While the dust particles of the ring appeared to extend inward toward Jupiter, probably all the way to the cloud tops, the ring had a hard outer edge, as if cut from cardboard.

the bright portion of the ring itself. The dust may be due to micrometeorites striking larger bodies in the ring.

Voyager 2's Jupiter encounter ended in September 1979, and scientists and engineers began preparing the intricate command sequences for the two encounters with Saturn.



THE JUPITER PICTURES

Jupiter and two of its largest satellites, Io and Europa, are captured by Voyager's cameras (A). Io is the red satellite at the left. Many Jovian storm systems are visible, including the Great Red Spot, the white ovals below it, and alternating dark and light cloud bands called belts and zones. The strongest winds—up to 400 kilometers (250 miles) an hour—are found at boundaries between belts and zones. Between opposing jet streams the clouds are turbulent. The area immediately below the wide, bright, white zone is an example of that turbulence. Wind shear stretches convective features into long plumes; one can be seen near the center of the photo. Holes in the clouds permit observation of deeper layers of the atmosphere. One such area is a bluish region north of the equator and left of the white cloud plume. The blue regions are strong emitters of infrared radiation coming from higher temperatures deep in the atmosphere. (B) Io (left) and Europa pass before the planet's Great Red Spot. The rim of the Great Red Spot circulates counter-clockwise in six days, while there is almost no circulation at the center. The long bright region between two white ovals (across center of picture) extends higher into Jupiter's atmosphere and is therefore colder than the surrounding clouds. Almost all the white ovals exhibit the same counter-clockwise motion as the Great Red Spot, which has been observed continuously for about 300 years; formation of the white ovals was first observed about 40 years ago.



28.4 million km (17.5 million mi)



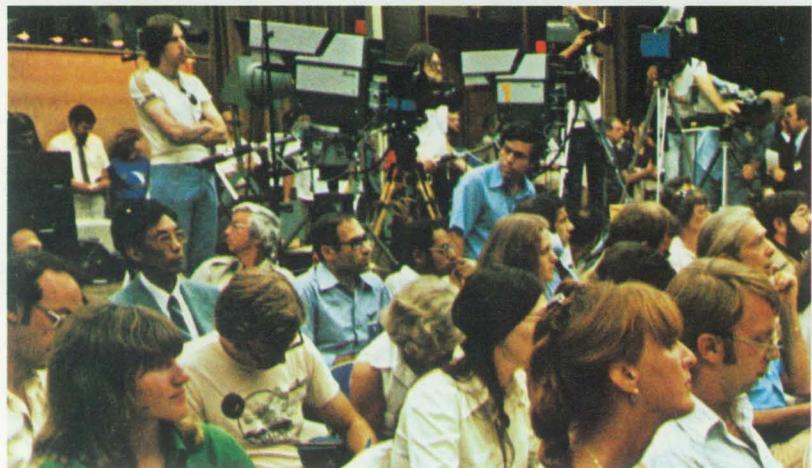
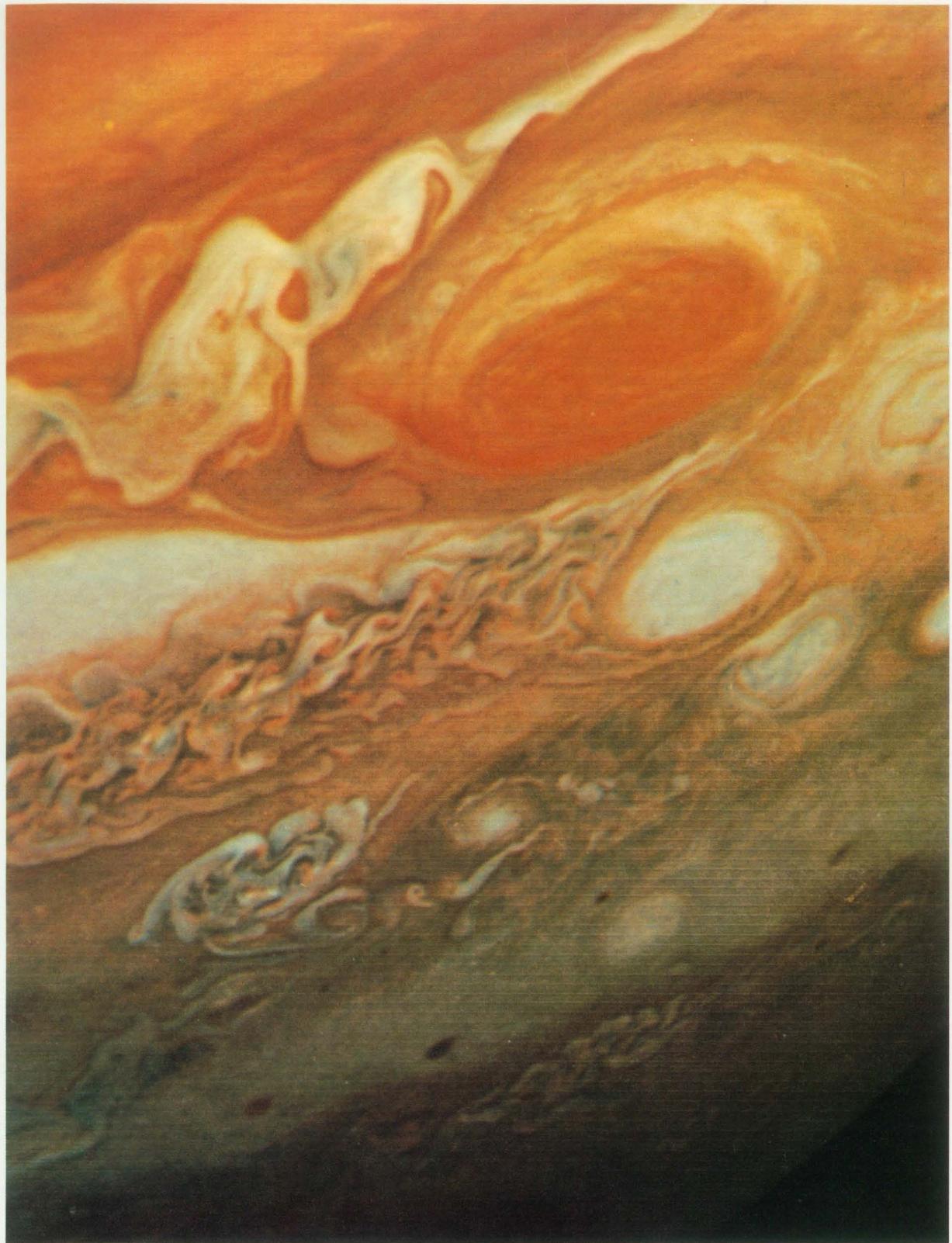
20 million km (12.4 million mi)

2/13/79

2/15/79

B

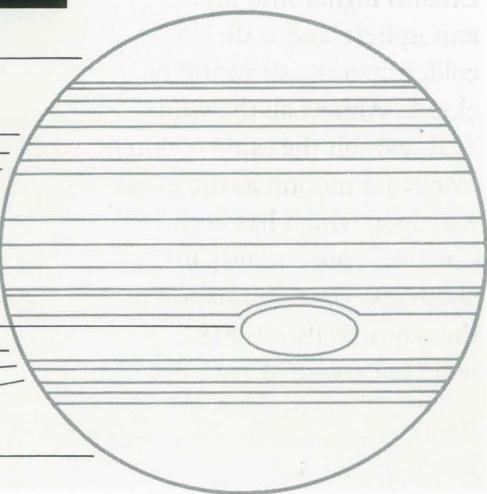
A



North Polar Region

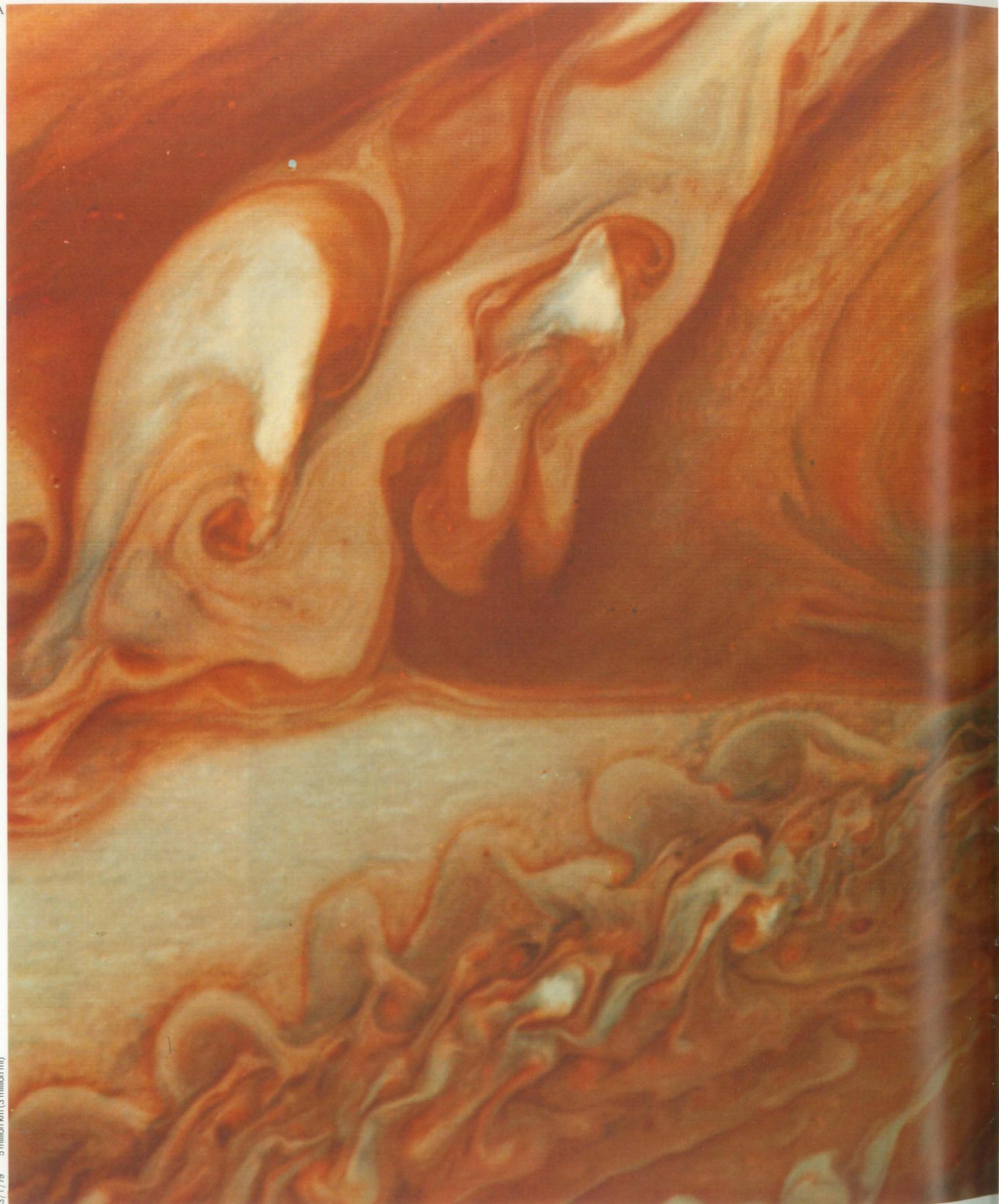
North Temperate Zone
 North Temperate Belt
 North Tropical Zone
 North Equatorial Belt
 Equatorial Zone
 Equatorial Band
 South Equatorial Belt
 Great Red Spot
 South Tropical Zone
 South Temperate Belt
 South Temperate Zone

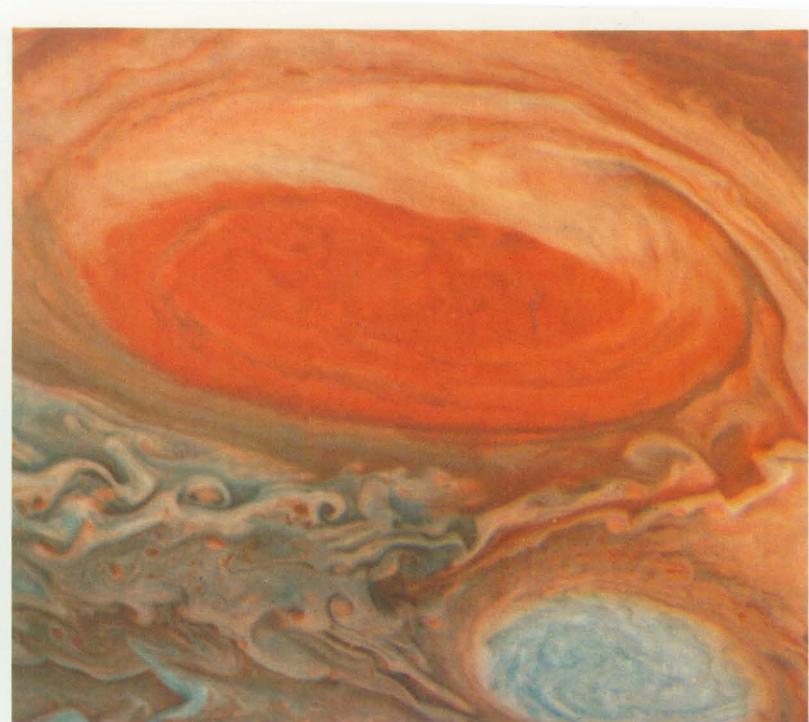
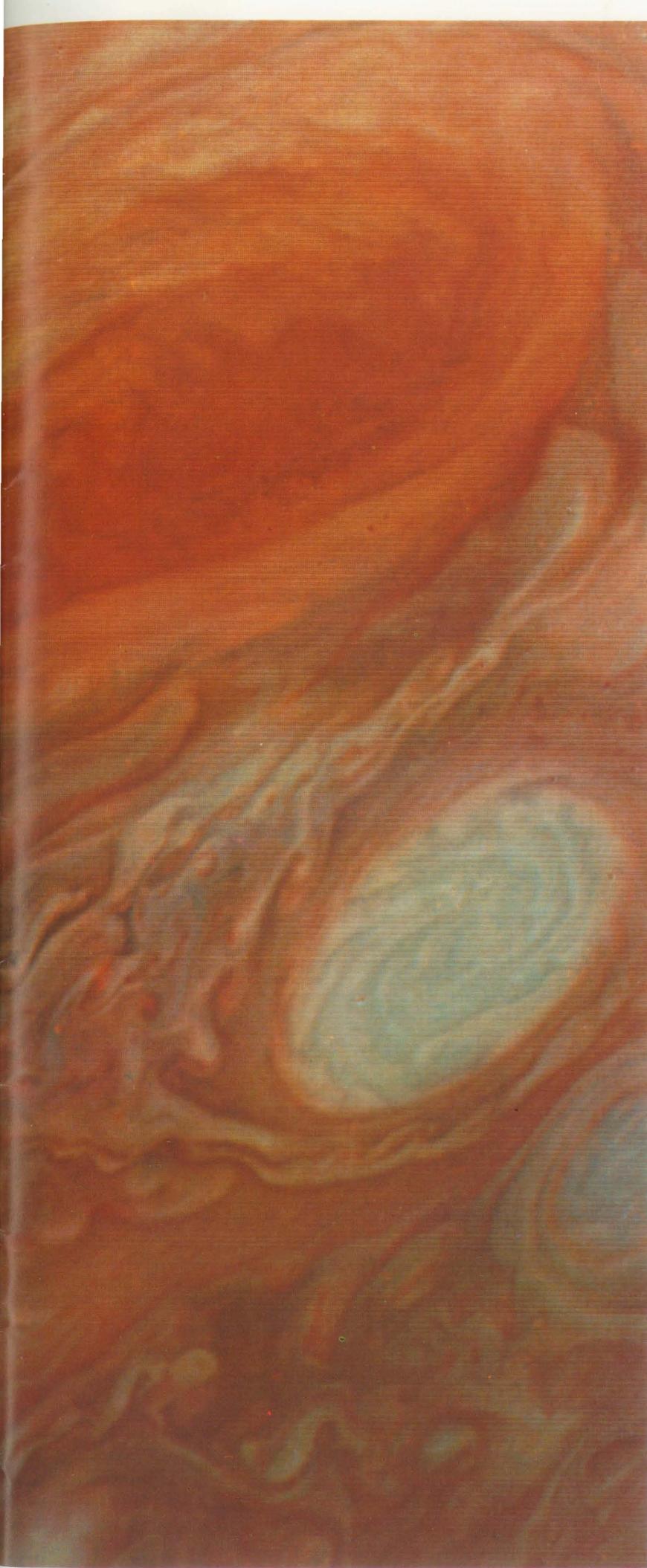
South Polar Region



A dramatic view of Jupiter's Great Red Spot and the surrounding area (C) shows cloud details as small as 160 kilometers (100 miles). The turbulent cloud pattern to the left of the Great Red Spot is a region of extraordinarily complex and variable winds. It has the appearance of liquids, such as oil and water, that do not mix. As relatively slow winds above the Red Spot flow past it, the smooth flow pattern is severely disturbed, creating the tumbled and twisted appearance. Some material from the region is also drawn into the Great Red Spot. Scientists don't understand why the cloud colors remain unmixed. As wind blows through the region between the Great Red Spot and the white oval, a turbulent pattern forms to the left. A lighter portion at the top of the Great Red Spot shows that some turbulent material is drawn into the Red Spot itself. Smaller amounts appear to interact similarly with the white oval. South polar regions at the bottom are darker than at mid-latitudes, probably because cloud circulation patterns there are different, and solar illumination is more oblique. The abundance of distinctive cloud patterns leads scientists to compare some aspects of Jupiter's winds with currents in the oceans of Earth.

A





B

1.8 million km (1.1 million mi)
3/79

Jupiter's Great Red Spot dominates a close-up Voyager photo (A) that has been compared to an abstract painting. The Great Red Spot, about 25,000 kilometers (16,000 miles) on its long axis, would cover three Earths. The Great Red Spot is higher than the surrounding clouds. The white oval immediately below the Great Red Spot is a similar, counterclockwise-rotating storm. Scientists do not know what causes the color differences, but they believe the distinctive color of the Great Red Spot may be due to minor constituents that come from deeper within the atmosphere. The Great Red Spot's center has the puffy appearance generally associated with little or no wind and cloud motion, while its outer rim shows the streamlined shapes of 360-kilometer-(225-mile-) per-hour winds. The white oval's inner spiral structure, seen in this photo for the first time, is also the result of counterclockwise winds. The white zone at left, at the same latitude as the Great Red Spot, disappears almost entirely as it moves past, then is regenerated to the east. The normal-color

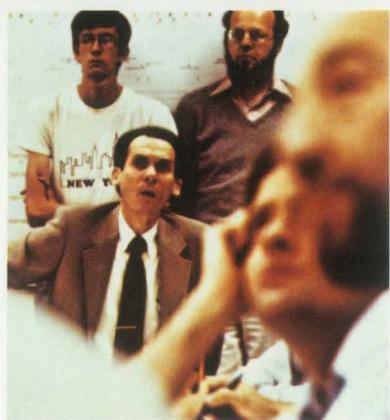
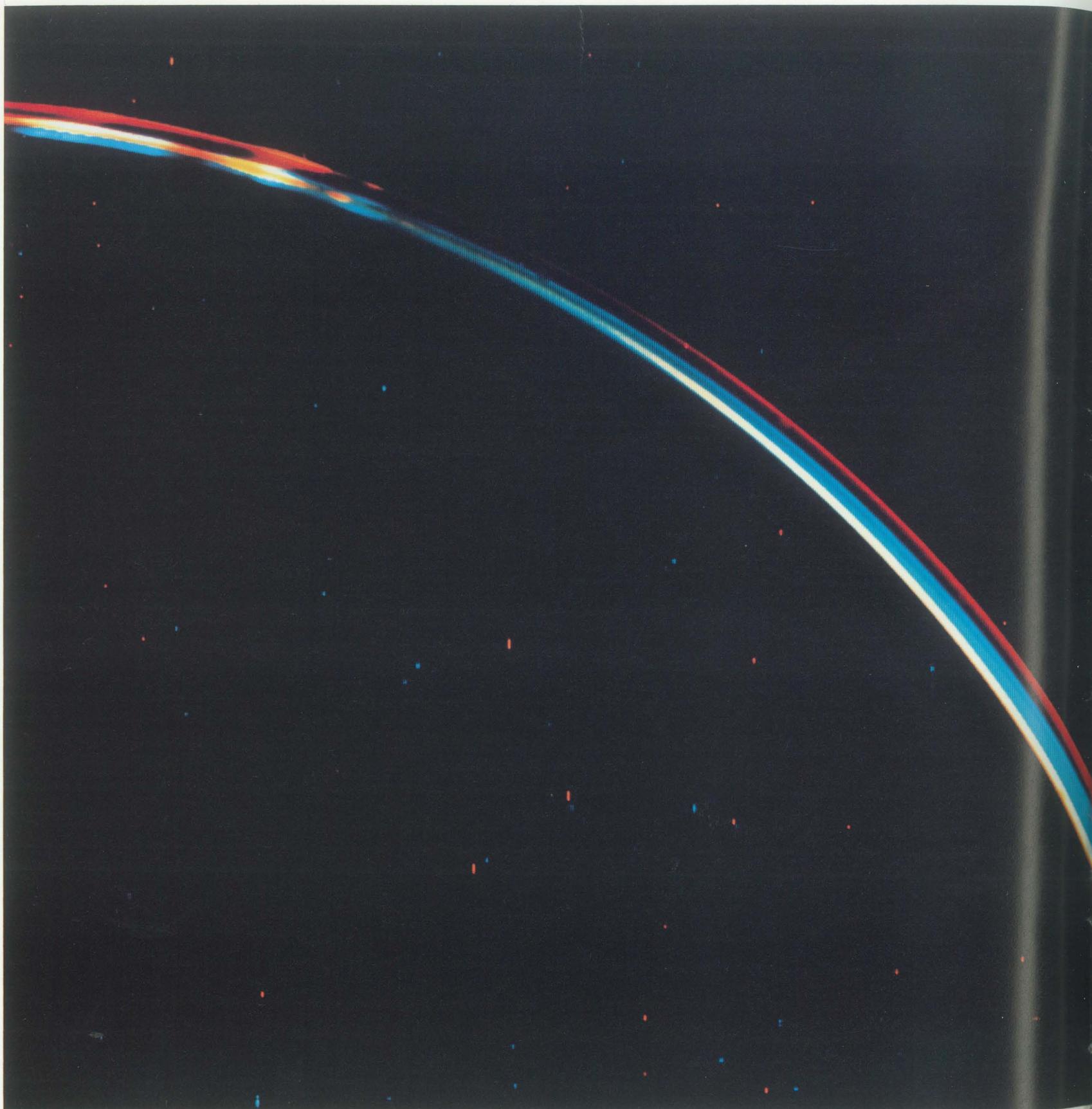


photo (B) shows a startling amount of color difference below and to the left of the Great Red Spot, which is partially obscured at the top by high, white, ammonia cirrus clouds. Because hurricane-like winds extend in a column above and below the Great Red Spot, the spot seems to act like a stationary object, producing eddies in adjacent clouds similar to eddies in a stream caused by an obstruction.

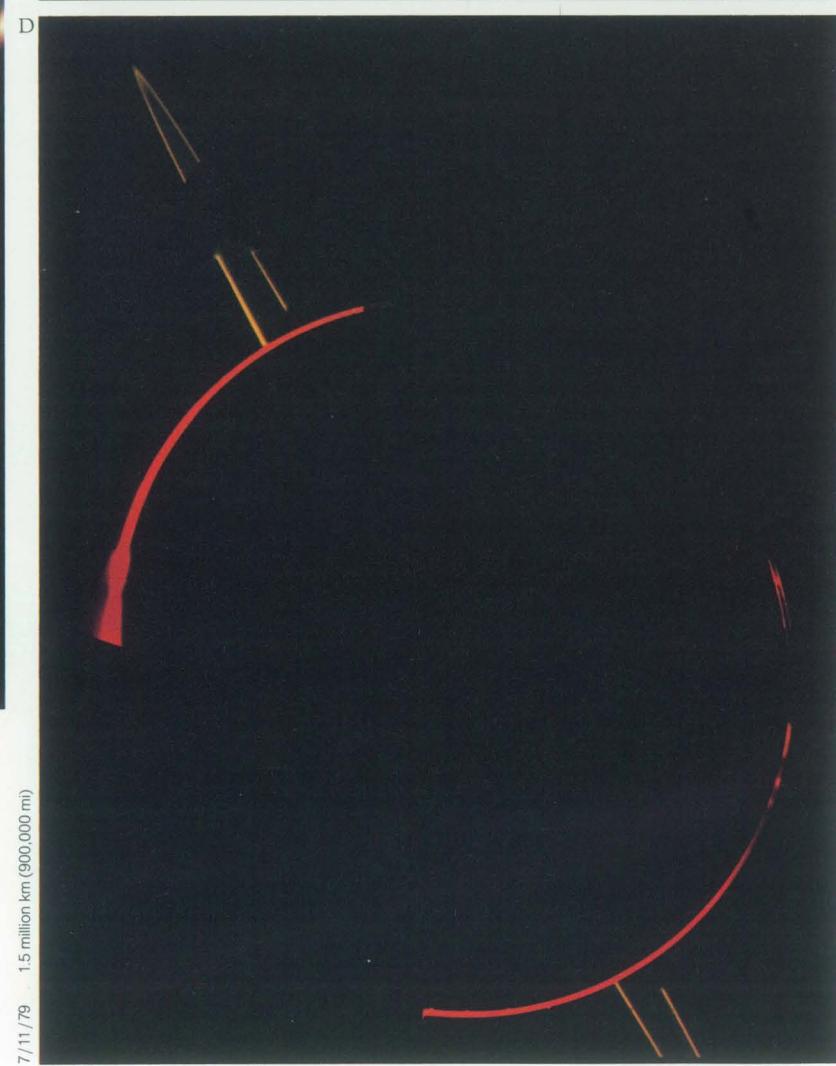
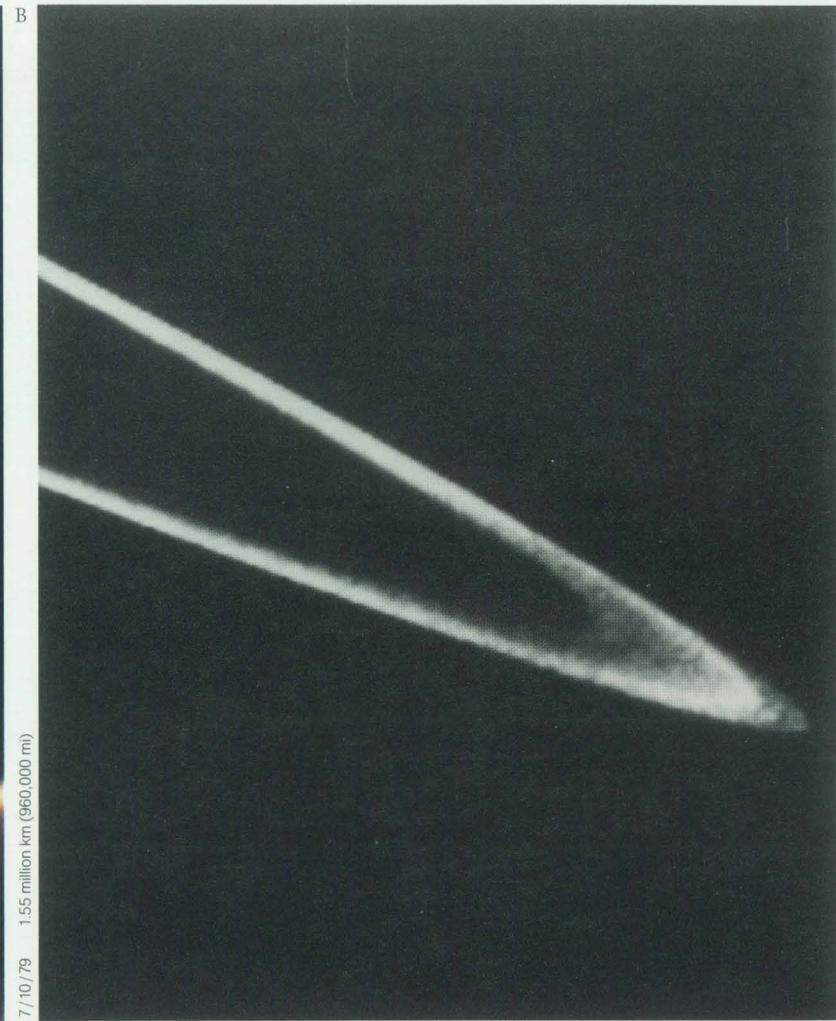


The Jovian ring sparkles as Voyager looks backward at the dark side of the planet (A). The upper portion, the closer segment, disappears where it enters Jupiter's shadow. The ring, mainly extremely fine dust particles, apparently comes from two tiny

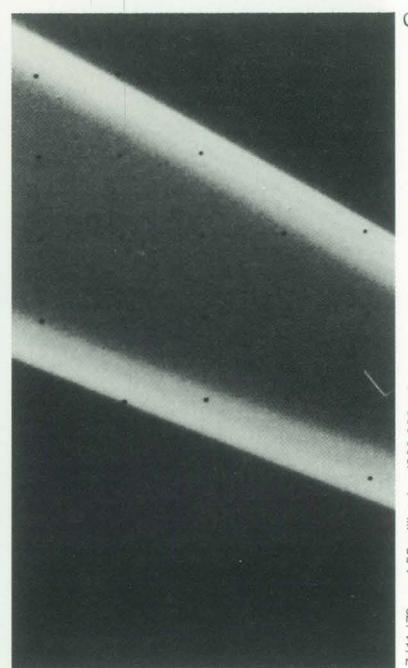
satellites near its outer edge; those satellites were also discovered by Voyager. The bright portion of the ring is about 5,200 kilometers (3,200 miles) wide. Jupiter's bright limb shows

as three separate color bands, because color pictures are assembled on Earth from black-and-white photos taken through color filters, and the spacecraft had moved between each photo. Computers on Earth registered the pictures to show the

ring; therefore the planet's limb failed to register. The ring has a diffuse halo of fine particles inside the two segments. The ring's extreme faintness dictated long camera exposures.



Jupiter's ring has a sharp outer edge (B), patrolled by two tiny satellites, while the inner edge fades gradually. A faint star trail (C) shines through the ring's inner halo. The halo is an area of extremely diffuse ring material extending inward to the top of Jupiter's atmosphere, indicating that the ring is continually losing material. The spots are reseau marks, engraved on the face of the camera's vidicon tube to allow scientists to reconstruct the pictures' geometry precisely. The bottom photo (D) is a different computer processing of the rings used to bring out slightly different details. Gaps in the ring are an artifact of joining several photos together.



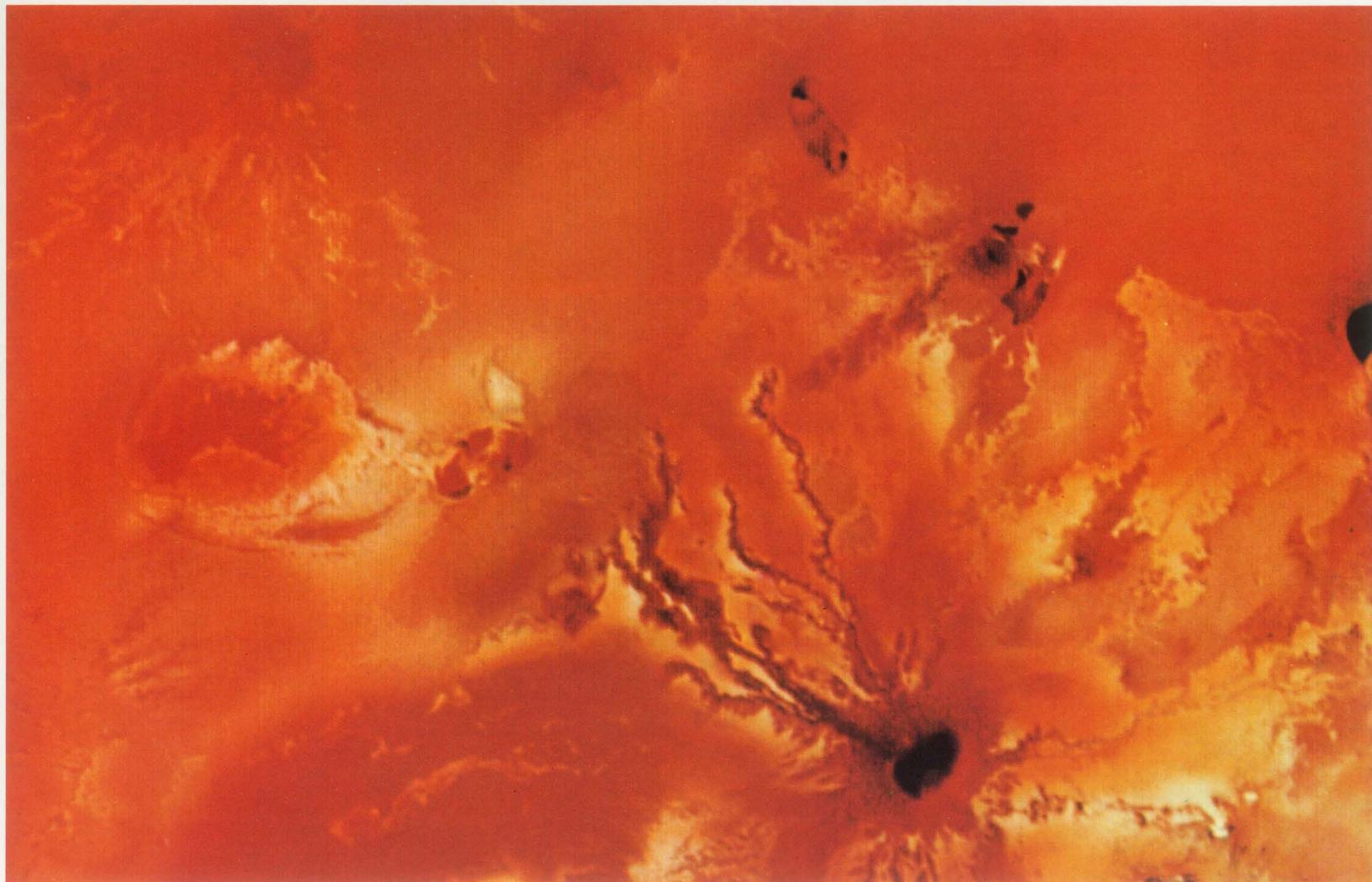
A



B



C



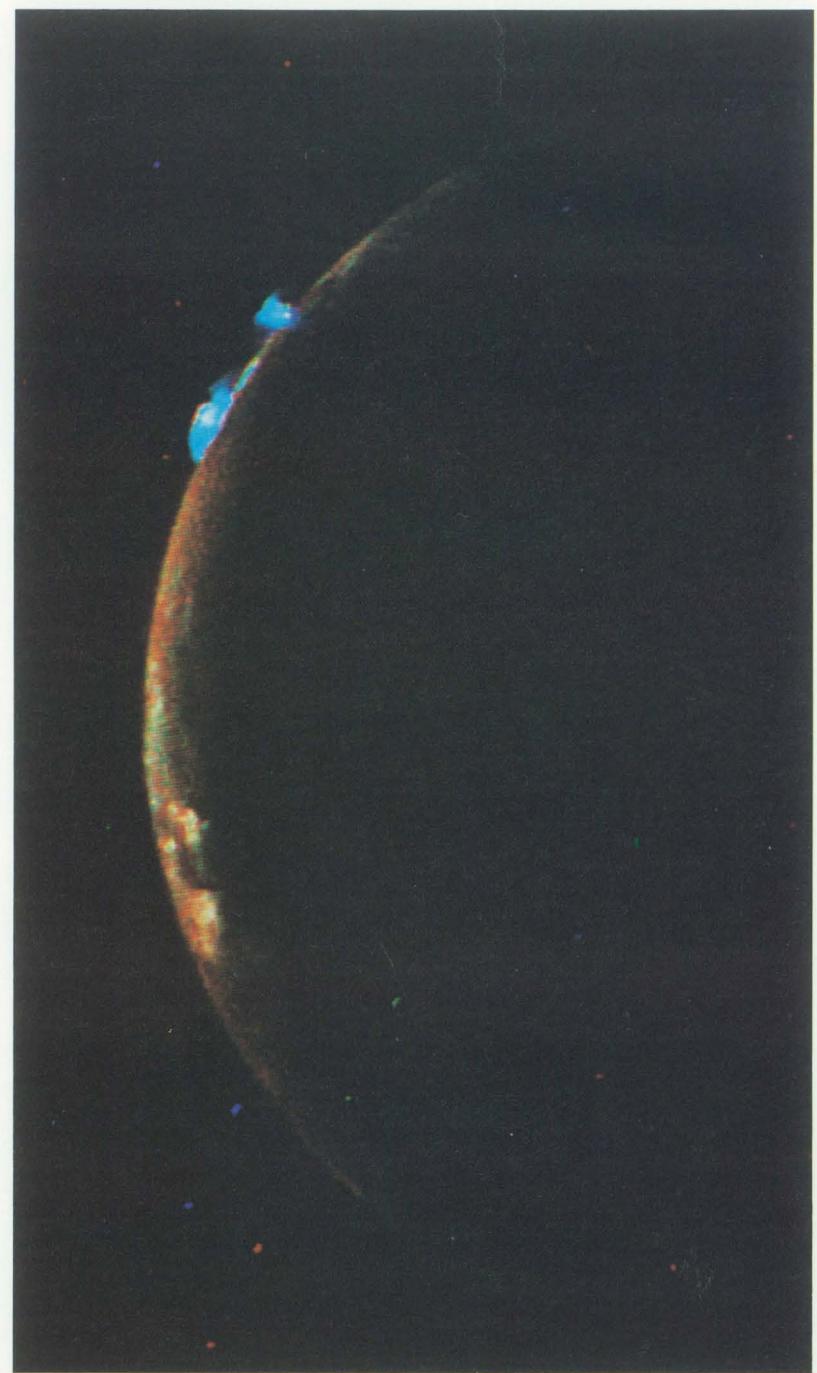
3/5/79 128,500 km (77,100 mi)

Io is the first body beyond Earth where scientists have seen volcanic activity in progress. The heart-shaped deposit (A) from the volcanic plume named Pele changed to an oval shape between encounters. Pele hurled ejecta 280 kilometers (175 miles) above Io's surface. Total width of the plume was 1,000 kilometers (620 miles). Sulfur dioxide gas has been identified venting from the volcanoes. The dark, U-shaped object (upper left) is probably a lava lake with an encrusted surface that may be

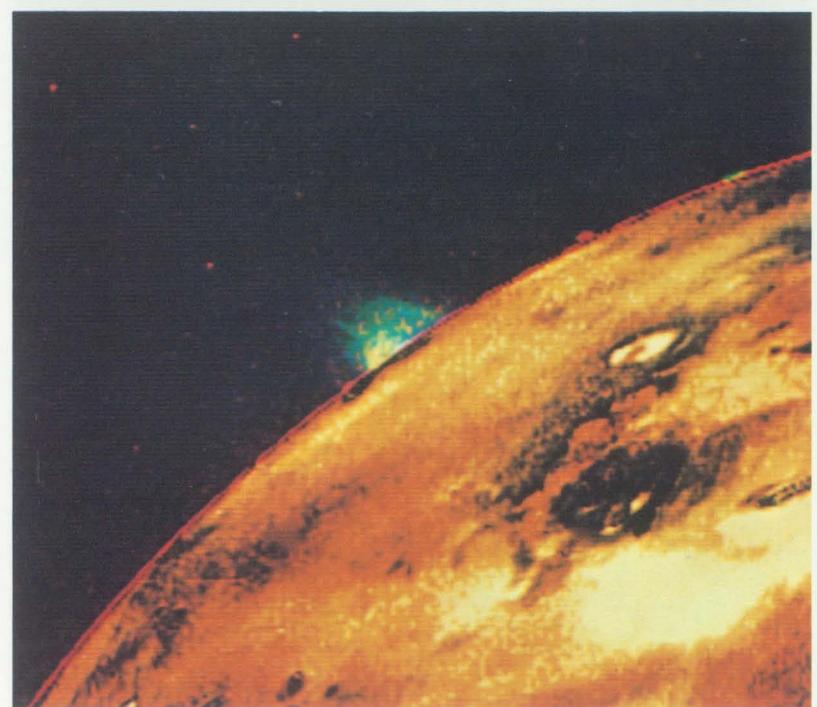
physically associated with the plume named Loki, next to it. The lake's temperature is in excess of 200°K (-99°F), about 80°K (144°F) higher than the temperature of the surrounding surface. Voyager 1 looked almost directly up at Io's south polar region (B) as it passed beneath. A variety of terrain types can be seen, including isolated mountains up to 10 kilometers (6.2 miles) high. No impact craters are visible on Io's surface, since constant eruptions continually resurface the satellite with sulfur and silicates. A close-up photo (C) shows two volcanic calderas and associated lava flows on Io. Io is the most geologically active body known in the solar system. It has a diameter of 3,632 kilometers (2,257 miles), similar to that of Europa and the Moon.



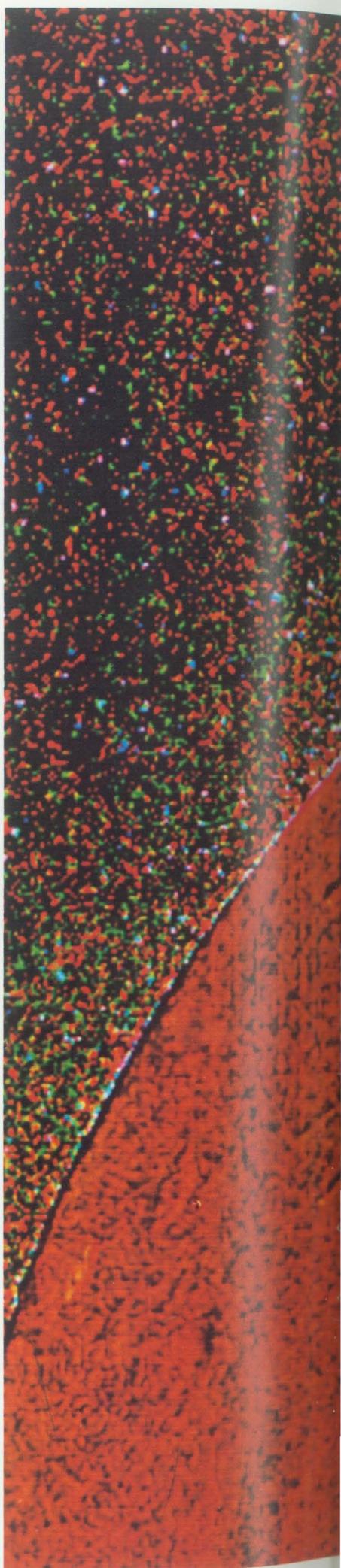
Voyager 2 monitored Io's volcanic activity continuously for six hours. One of those photos (A) shows two blue volcanic plumes standing about 100 kilometers (62 miles) above the surface. Io's activity is a result of extreme tidal pumping: The satellite's elliptical orbit around Jupiter, caused by resonance with Europa and Ganymede, creates differences in Jupiter's gravitational pull on Io (at different locations in Io's orbit), which flex Io's surface and the region just beneath. The result is mechanical heating that melts almost the entire body. A volcano (B) spews material at a velocity of about 3,300 kilometers (2,000 miles) per hour. Mount Etna, one of Earth's most explosive volcanoes, ejects material at only about 65 kilometers (40 miles) an hour. The brightness in this photo has been enhanced, while color has been preserved. Loki appears in a false-color image (C), in which ultraviolet light, sensitive to the smallest ejecta particles, has been processed in blue to show the symmetrical structure of the plume. Eight or nine volcanoes were erupting as Voyager 1 flew past; at least six were still erupting when Voyager 2 arrived four months later.

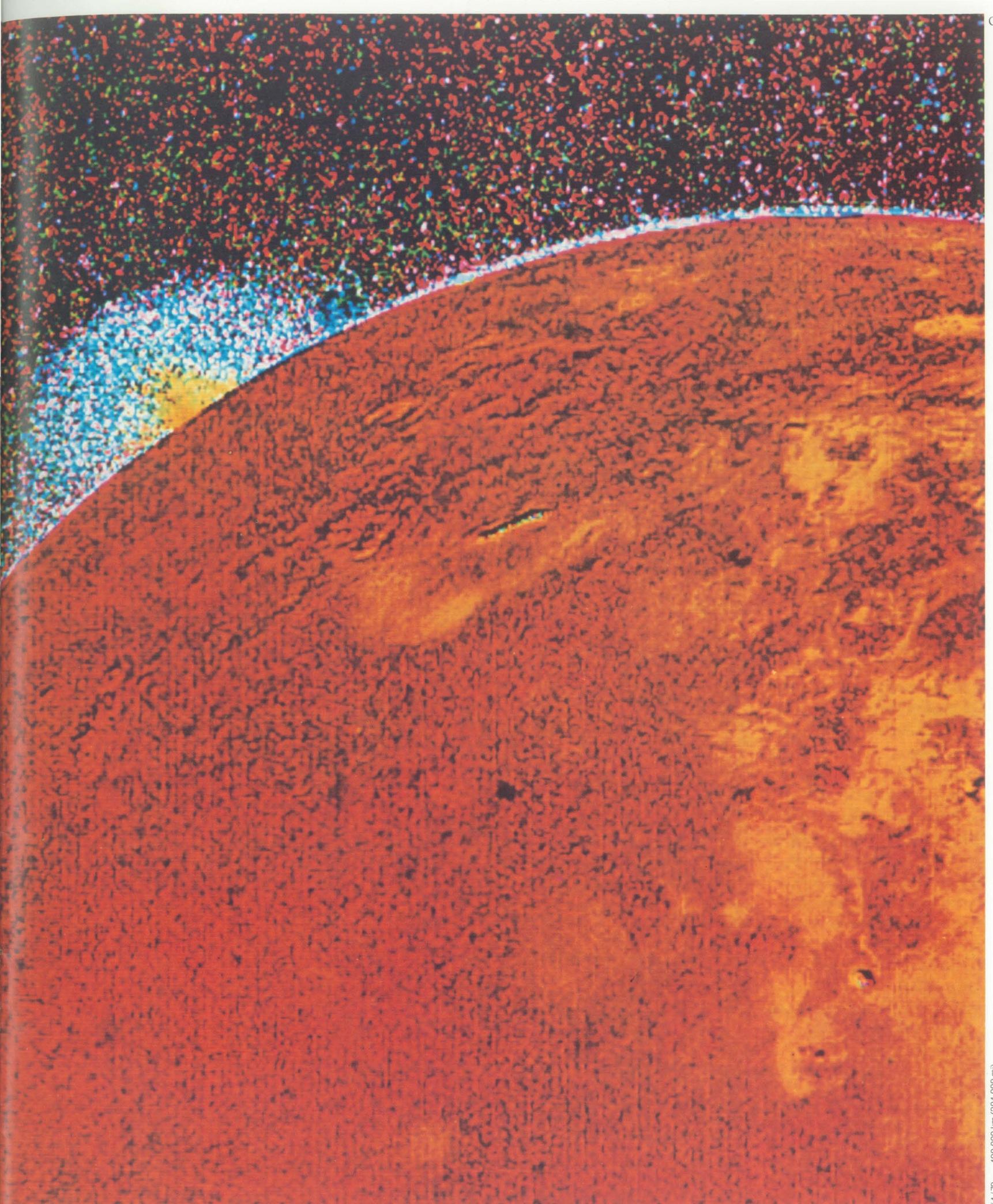


7/9/79 1.2 million km (750,000 mi)

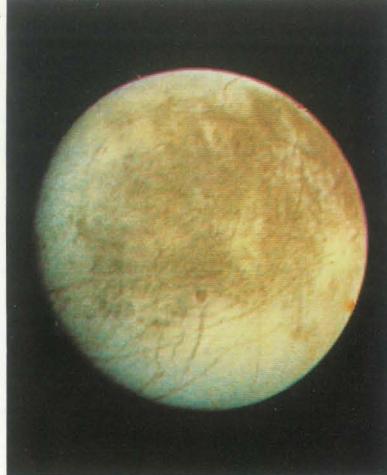


3/4/79 490,000 km (304,000 mi)

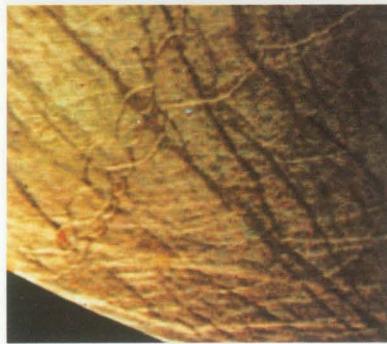




A



B



C



Europa also provided scientists with puzzling phenomena. The ice-coated satellite (A) is remarkably smooth, and shows few craters. The surface consists primarily of uniformly bright terrain, mainly water ice, crossed by linear markings with no topographic relief, except for light lines such as the chainlike ridges (B), which are only a few hundred meters high. They could result from cracking of the surface and extrusion of fresh ice from below. Scientists believe tidal forces similar to those on Io are responsible for those processes, although tidal heating is not sufficient to cause active volcanoes as on Io. A similar light-colored ridge meanders across Europa's surface (C).

Europa's surface ice could be up to 100 kilometers (62 miles) thick; the rest appears to be rocky and metallic. Europa's diameter is 3,126 kilometers (1,942 miles).

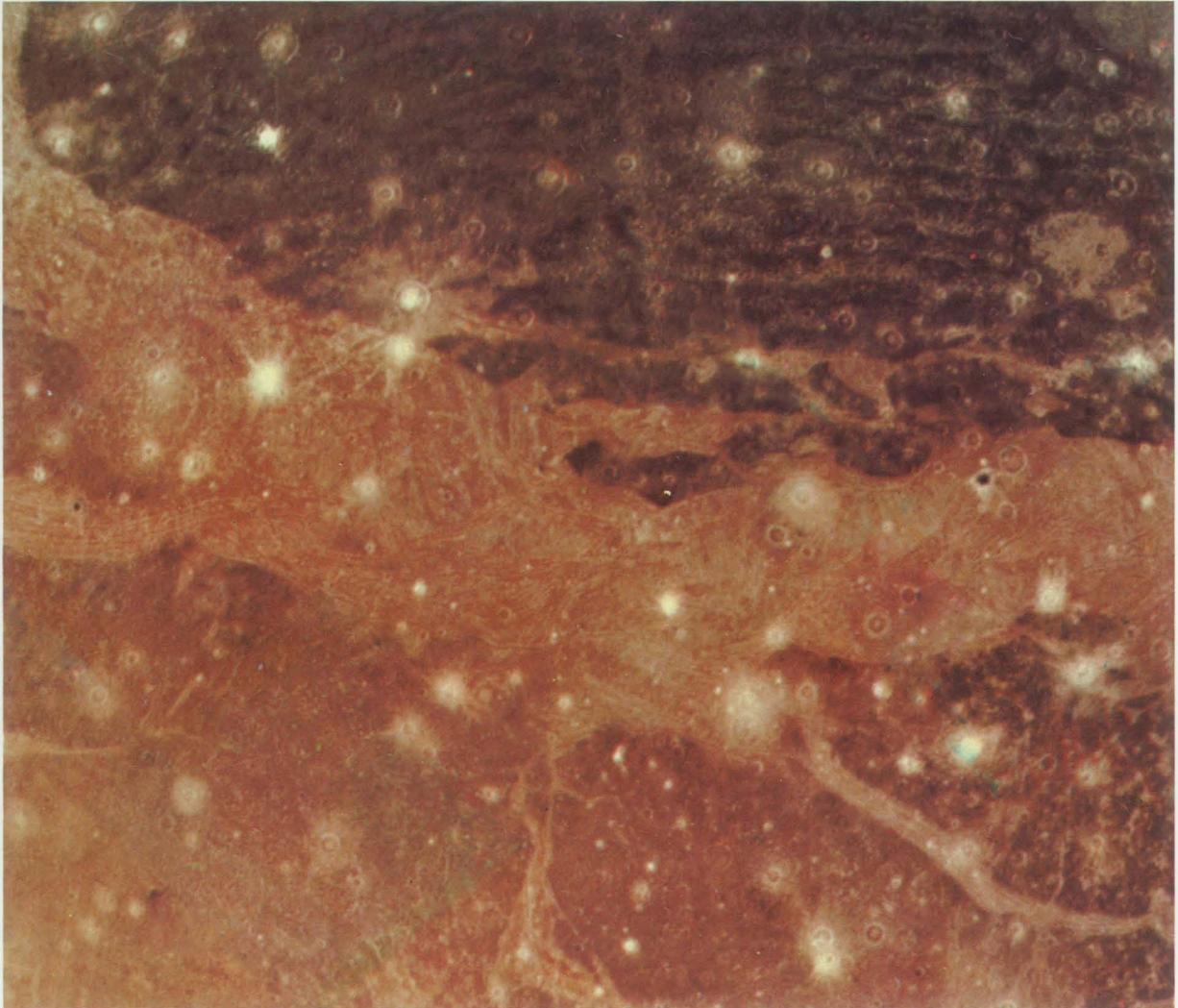
A

7/7/79 1.2 million km (750,000 mi)



B

7/8/79 312,000 km (194,000 mi)



The surface of Ganymede is one of great diversity, indicating several periods of geologic activity. Many dark areas (A) are heavily cratered and probably date from the time of an early bombardment more than 4 billion years ago. Other regions are clearly a product of intense internal geologic activity, which happened over the next few hundred million years. The latter regions generally have high albedo and consist of many parallel lines of mountains and valleys (B) intersected by what appear to be faultlike discontinuities. Craters surrounded by bright ejecta blankets are probably much younger than the dark craters. Though its surface is much darker than Europa's, Ganymede is half water ice and half rock, resulting in a density about two-thirds that of Europa. Scientists had thought Titan was the largest satellite in the solar system, but Voyager measured Ganymede and later measured Titan, and found that Ganymede is larger—the largest satellite in the solar system. Ganymede's diameter is 5,276 kilometers (3,278 miles); Titan's diameter is 5,150 kilometers (3,200 miles). Ganymede's surface is a frozen record of its tectonic history—the geologic processes by which half of the ancient, darker surface was replaced by the younger, brighter grooved terrain.



7/8/79

A



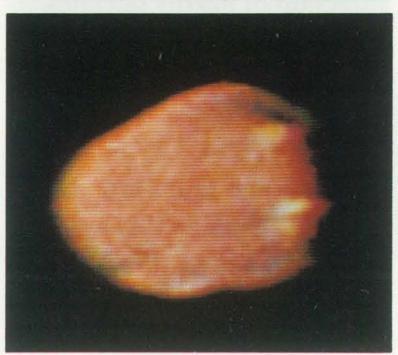


The outermost Galilean satellite is Callisto. Although similar in size and composition to Ganymede, its surface is strikingly different. Obvious at first glance are the many craters on Callisto's surface (B), which indicate that the surface must date back to the late torrential bombardment period some four billion years ago. There is no evidence for any further geologic activity, once Callisto's surface froze. Because the impact craters formed in an icy surface, many of the larger ones have sagged back nearly to their original surface level, since ice is not strong

enough to bear the weight. More recent bombardment is evident in craters that are surrounded by bright rays, which are fresh ice overlaid on the older, darker surface. Also obvious (A) is a huge, ancient impact structure, a multiringed feature that is, in some respects, similar to large impact basins on the surfaces of the Moon and Mercury. However, there is no central basin, just a bright, circular patch surrounded by at

least 10 ridges with radii extending up to 1,500 kilometers (930 miles) from the center. The feature formed when an object collided with Callisto, fracturing and melting the surface, which quickly refroze again. Since Callisto is half water ice, the basin was unable to hold its shape, slowly slumping back until only shadows of the surrounding rings remain. Callisto is the second largest Galilean satellite, with a diameter of 4,820 kilometers (2,995 miles), and is larger than Mercury and Pluto.

Amalthea is darker and smaller than any Galilean satellite, and orbits closer to Jupiter than Io does. The tiny satellite has an irregular shape (C, D, and E). One Voyager scientist said he doubted "if one astronomer in 100 had ever seen Amalthea." Amalthea was the first intermediate-size planetary object photographed in detail. It is about 270 by 165 by 150 kilometers (168 by 103 by 93 miles), 10 times larger than the Martian satellite Phobos. Its long axis always points to the center of Jupiter. The red color is real and has been computer enhanced to make it brighter; it reflects only about 5 percent of the sunlight that strikes it. Amalthea is deeply embedded in Jupiter's intense radiation field, which undoubtedly alters surface materials.



THE FIRST SATURN ENCOUNTER

The results of the two Jupiter encounters had a cautionary effect on planning for the Voyagers' encounters at Saturn. Astronomers had observed Jupiter extensively from Earth, but were nevertheless surprised by the Voyager discoveries. Their Earth-based observations of Saturn had been less complete, because of Saturn's greater distance and because less time had been spent at the telescopes. Therefore the scientists were a little wary of predicting what they would find when the Voyagers arrived at the ringed planet.

As the summer of 1980 continued, Voyager 1 began its encounter with Saturn. The planet appeared almost featureless in early photos. It was surrounded by the three classic rings that had always been studied from Earth: the outer A-ring, the middle and brightest B-ring, and the gossamer, innermost C-ring. (Other faint rings had been, and would be, discovered from Earth, from Pioneer 11, and by the Voyagers. They would be called D-, E-, F-, and G-rings.) But it appeared, in early photos, as if there were not just three rings, but scores, then hundreds, and finally thousands of thin ringlets. It would turn out that they were not individual rings separated by gaps; some of the variations were caused by the gravitational attraction of nearby satellites, pulling millions of particles into motion, spiraling outward across the rings like waves in an ocean. The causes of other variations are still unknown; a very few may be due to tiny satellites embedded within the rings. Saturn's rings are dynamic, changing with every passing day.

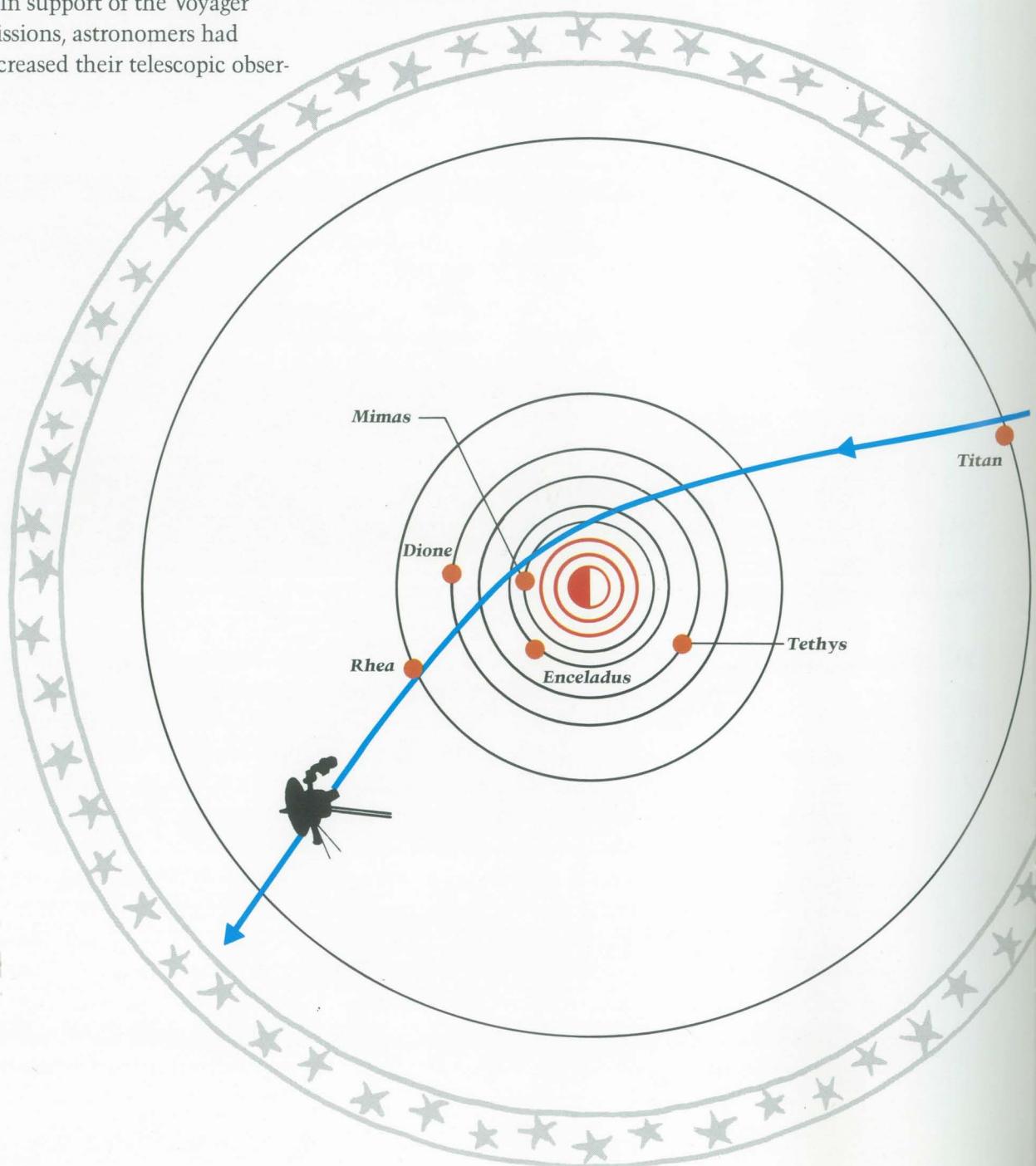
The photos from Voyager 1 also revealed other baffling phenomena—dark features that resembled spokes in the bright B-ring. The spokes appeared to rotate around Saturn with the ring. Here again was something that defied quick explanation. The speed at which one object orbits another depends on its distance from the primary body. It moves rapidly if it is near; ever more slowly at successively greater distances. While some spokes appeared to follow that set of physical laws, others looked as if they kept their radial form as they circled Saturn.

In support of the Voyager missions, astronomers had increased their telescopic obser-

vations from Earth, and in their photographs they discovered new satellites. Some were small—only 100 kilometers across or less. One appeared to orbit Saturn at the same distance as a large known satellite, Dione. Two others orbited the planet just beyond the edge of the narrow F-ring, which dwells outside the well-known A-, B-, and C-rings.

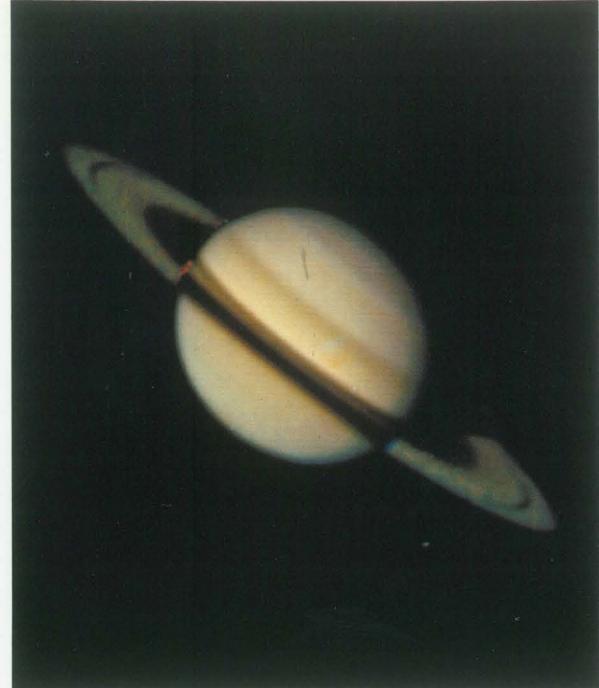
As Voyager 1 closed in on Saturn, more satellites were seen, until a total of six had been found—three

from Earth observations and three by Voyager. Two that were discovered in Voyager images appeared to shepherd the narrow F-ring. Two more, discovered from Earth, had appeared to share the same orbit. Inspection of Voyager photos, however, showed that the satellites' orbits are about 50 kilometers (31 miles) apart; a little calculation yielded the astonishing prediction that, as the two satellites approached each other in January 1982, they would trade orbits and continue on their way, to resume their game of





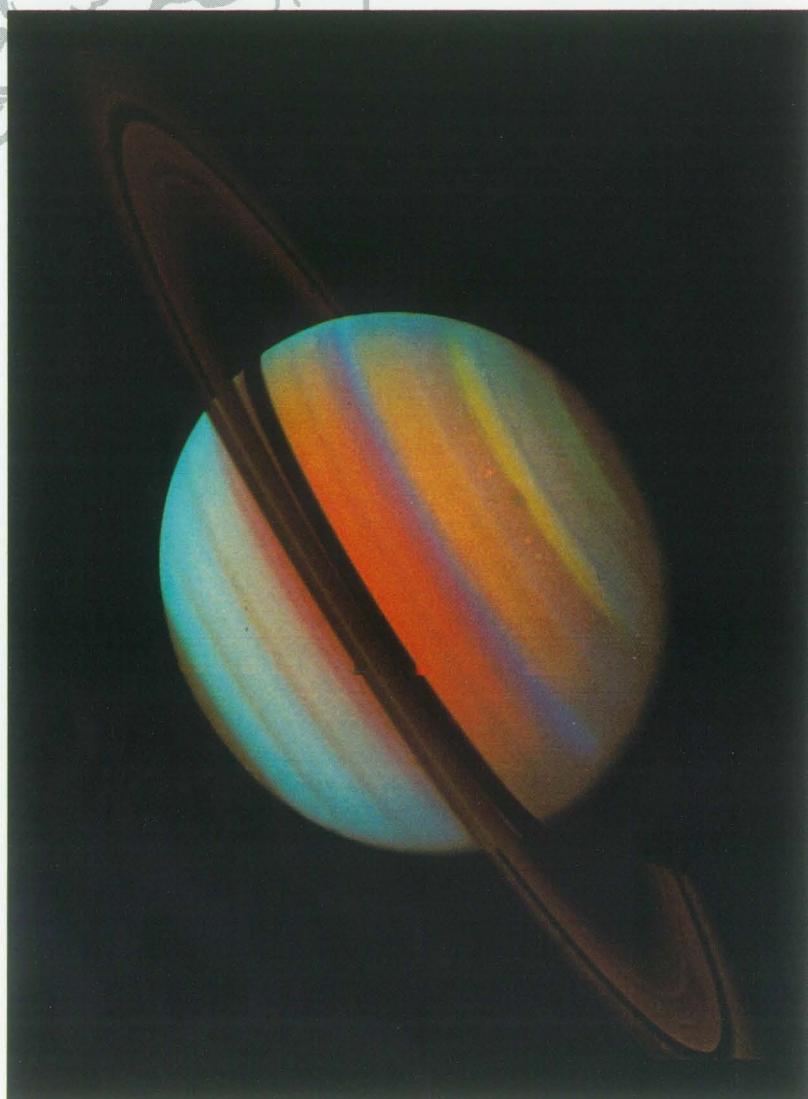
An early Voyager picture of Saturn shows about the same amount of detail as a good Earth-based telescopic photograph.



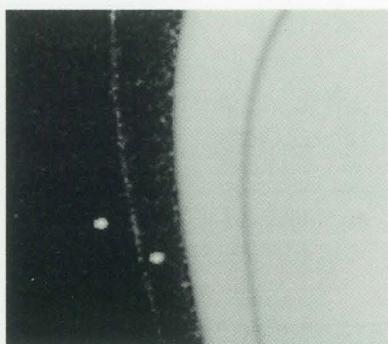
6/24/80 187 million km (116 million mi)

"Physics is experience, arranged in economical order."

ERNST MACH



Saturn appears to glow in this false-color rendition of a photo taken through ultraviolet, green, and violet filters.



8/15/81 10.5 million km (6.6 million mi)

10/18/80 33.5 million km (21 million mi)

Two tiny satellites shepherd Saturn's F-ring. The F-ring is multistranded and kinked in some places.

musical chairs the next time they approached.

A day before Voyager 1 swept by Saturn, it flew within 4,000 kilometers (2,500 miles) of the huge satellite Titan and passed directly behind it, making what scientists had predicted would be extremely important observations. Titan was shrouded by a thick, opaque haze that completely obscured its surface from the cameras. But the infrared instrument and the spacecraft radio probed the atmosphere to measure the diameter of the satellite and the thickness, temperature, and composition of its atmosphere.

Titan's atmospheric pressure, Voyager found, is greater by 60 percent than Earth's. In addition to the methane that had been detected from Earth, Voyager 1 found the atmosphere's major constituent is nitrogen, which is not detectable from Earth. The discovery is important because nitrogen appears to be rare except on Earth, and it is absolutely necessary for biological activity, as nitrogen is one of the primary constituents of living matter.

The methane could possibly play much the same role on Titan's surface as water plays on Earth—as a gas, a liquid, and a solid. Rivers and lakes of methane may reflect a smoggy, orange sky above icy mountain ranges. Clouds may drop methane rain or snow. Voyager's instruments showed that continuing organic chemistry converts some of the methane to ethane, acetylene, ethylene, propane, methyl acetylene, and (when combined with the nitrogen) hydrogen cyanide and other nitrogen-bearing compounds.

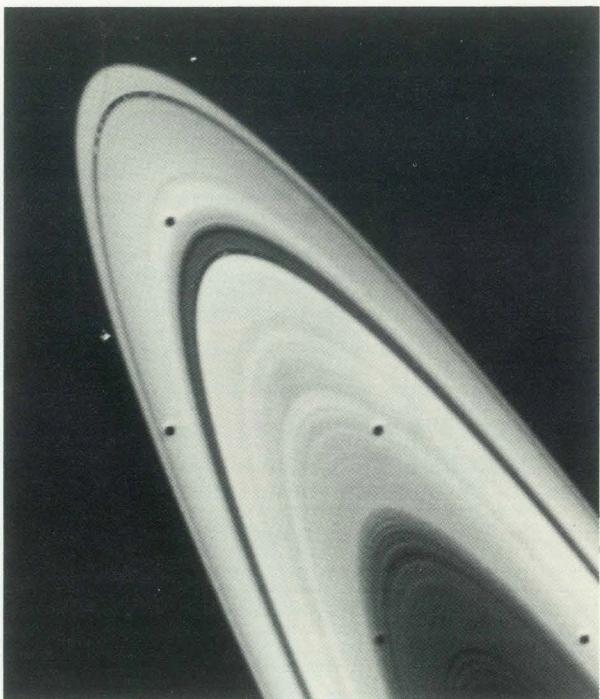
The hydrogen cyanide is an especially important molecule, since it is a building block of

amino acids, essential ingredients of life. Titan's low temperature, however—about 95°K (−288°F)—inhibits the complex organic chemistry that could lead to formation of life.

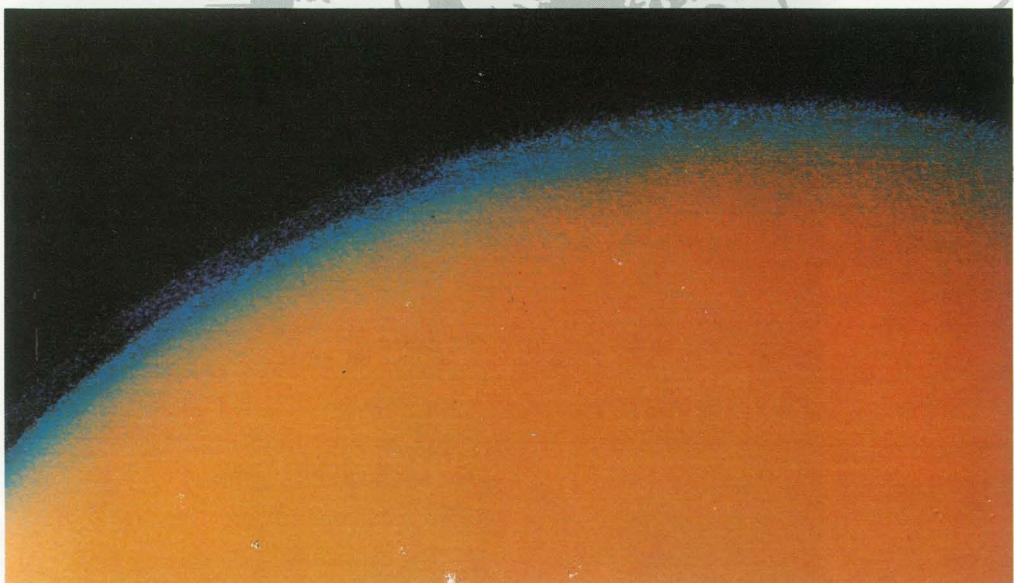
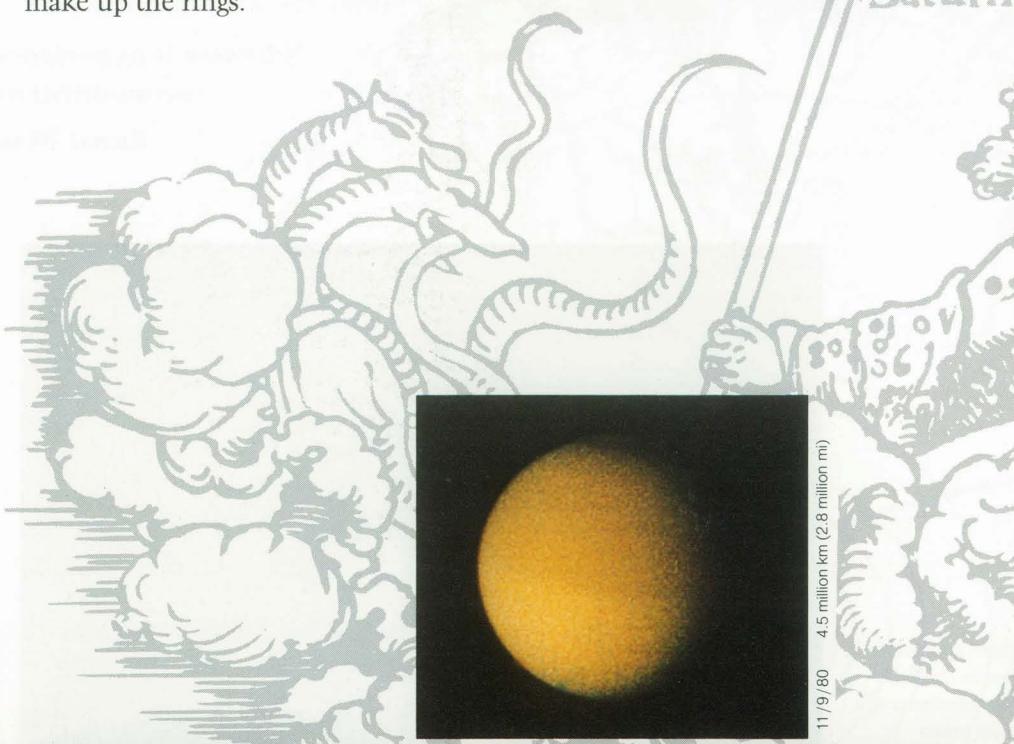
Once beyond Titan, Voyager 1 flew past Saturn and briefly disappeared behind it. En route to Earth the radio signals penetrated Saturn's atmosphere and passed through the rings. Measurements of the way the atmosphere altered the signals, and the rings scattered them, would tell much about the atmosphere and help determine the sizes of particles that make up the rings.

Saturn's escort of satellites is apparent as Voyager draws near. The Saturn system provided a cascade of discoveries. ▷

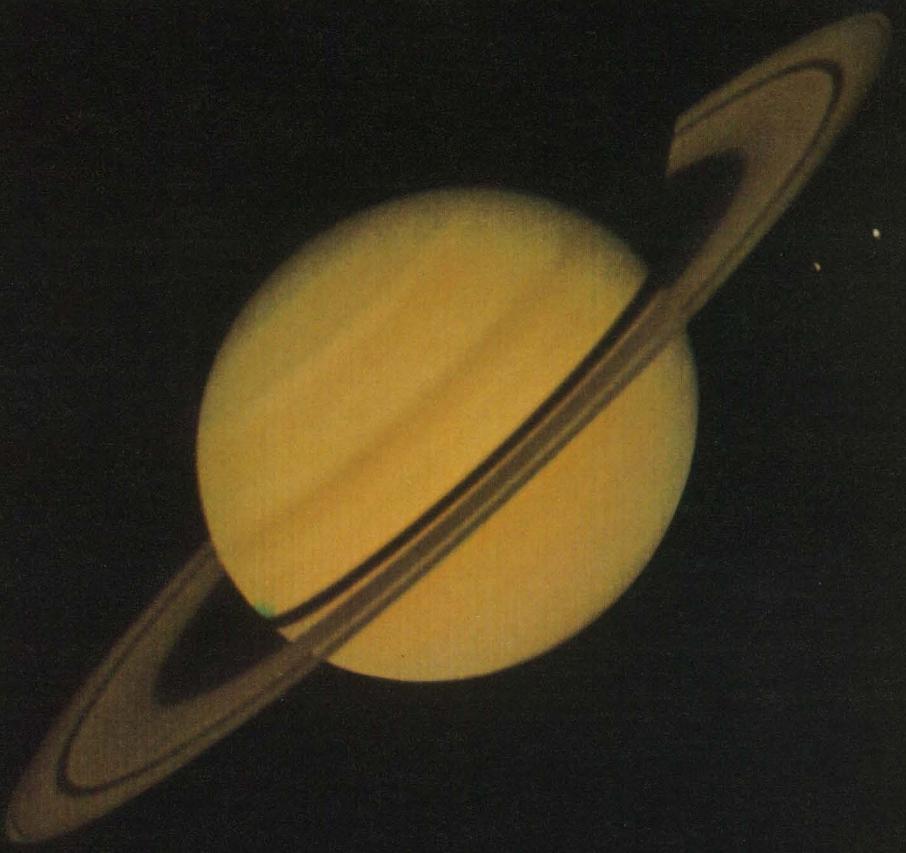
Saturn's rings, beautiful through any Earth-based telescope, reveal new structure in this Voyager photo.

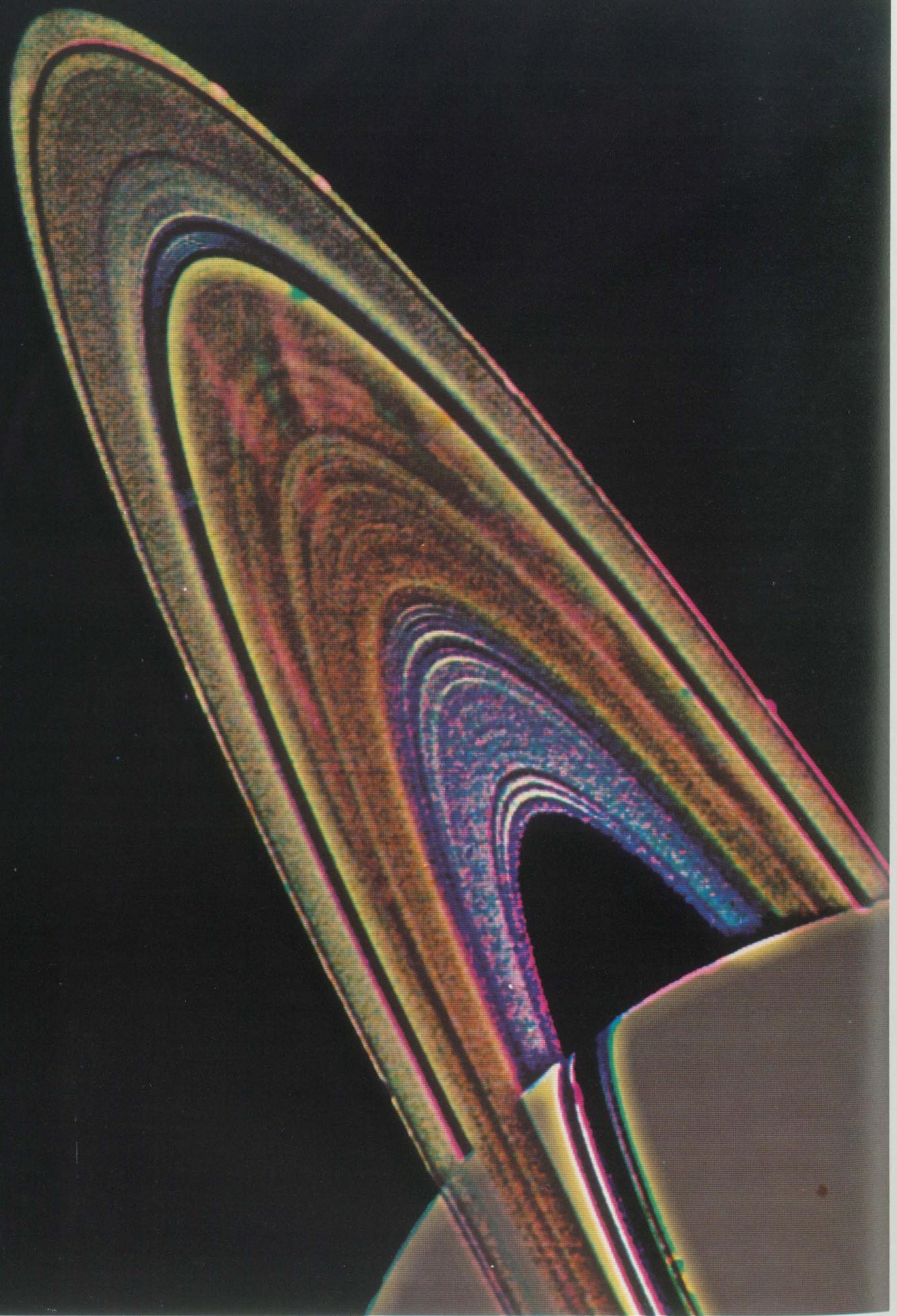


Saturnus



Titan, Saturn's largest satellite, has a dense atmosphere of nitrogen and methane, and is swathed in a thick, orange photochemical haze.



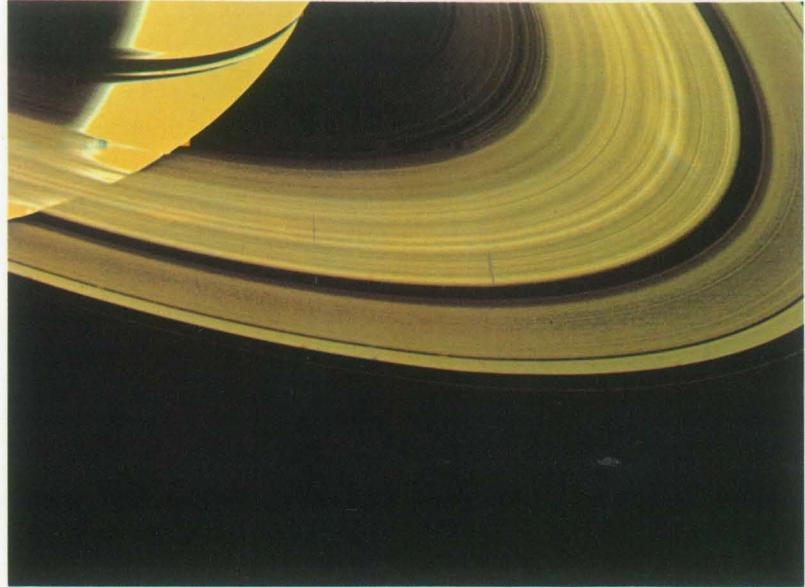


The radio experiment indicated the A-ring's average particles are about eight meters (25 feet) in diameter, while those in the C-ring are about two meters (six feet). The radio signal transmitted by Voyager through the B-ring was too weak to permit a similar analysis of that ring, but scientists believe that particles there are larger than in the A-ring. They hasten to add, however, that they believe that all the rings are seeded with much smaller particles; the radio signals pass right by the smaller bits of ice without being affected by them.

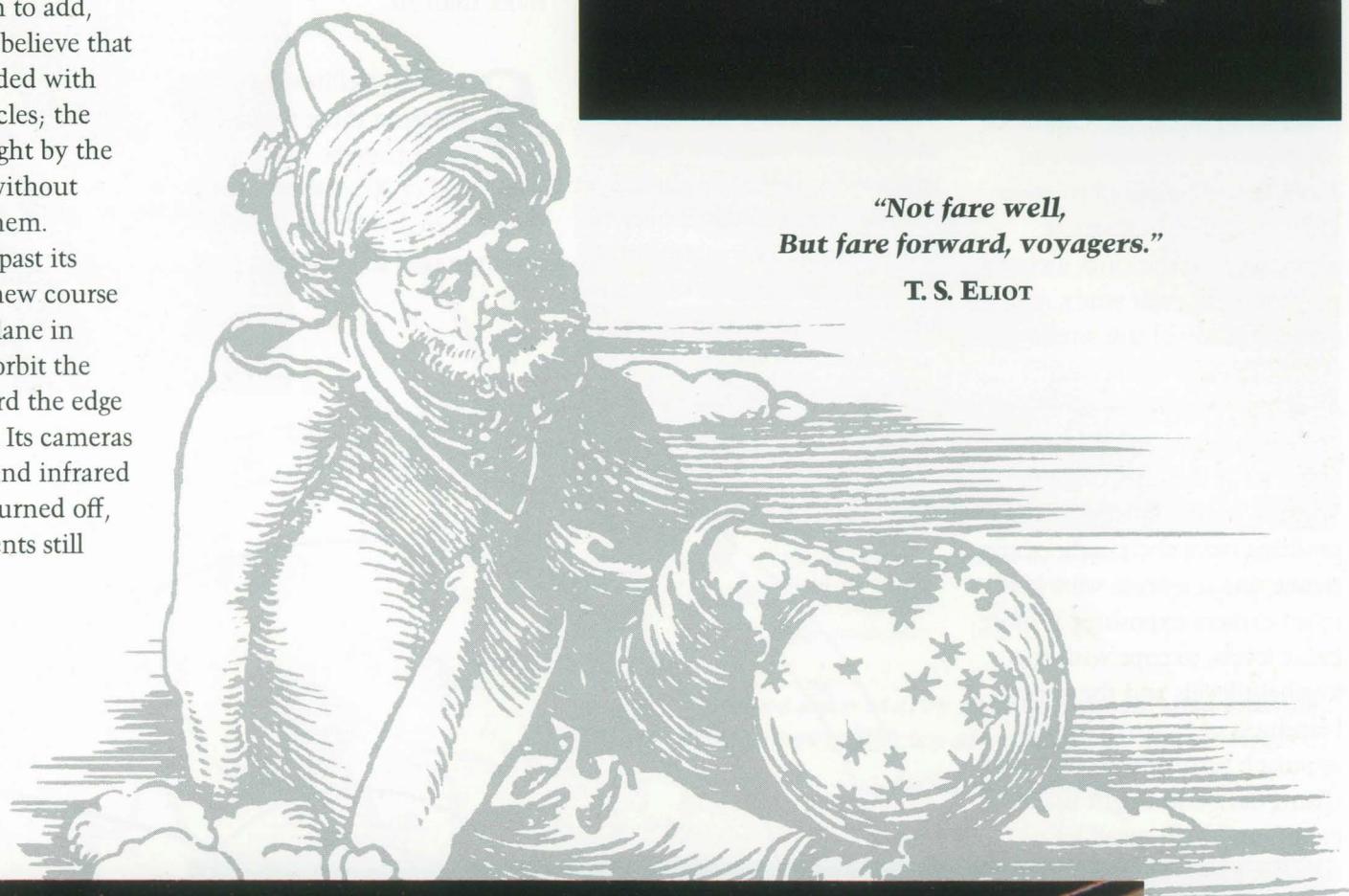
Voyager 1 swept past its targets and took a new course upward from the plane in which the planets orbit the Sun, outward toward the edge of the solar system. Its cameras and its ultraviolet and infrared instruments were turned off, but other experiments still

probe for galactic cosmic rays, the edge of the solar system, and the beginning of interstellar space.

Saturn shines through its rings. Voyager took this picture as it streaked away from the planet after closest approach.



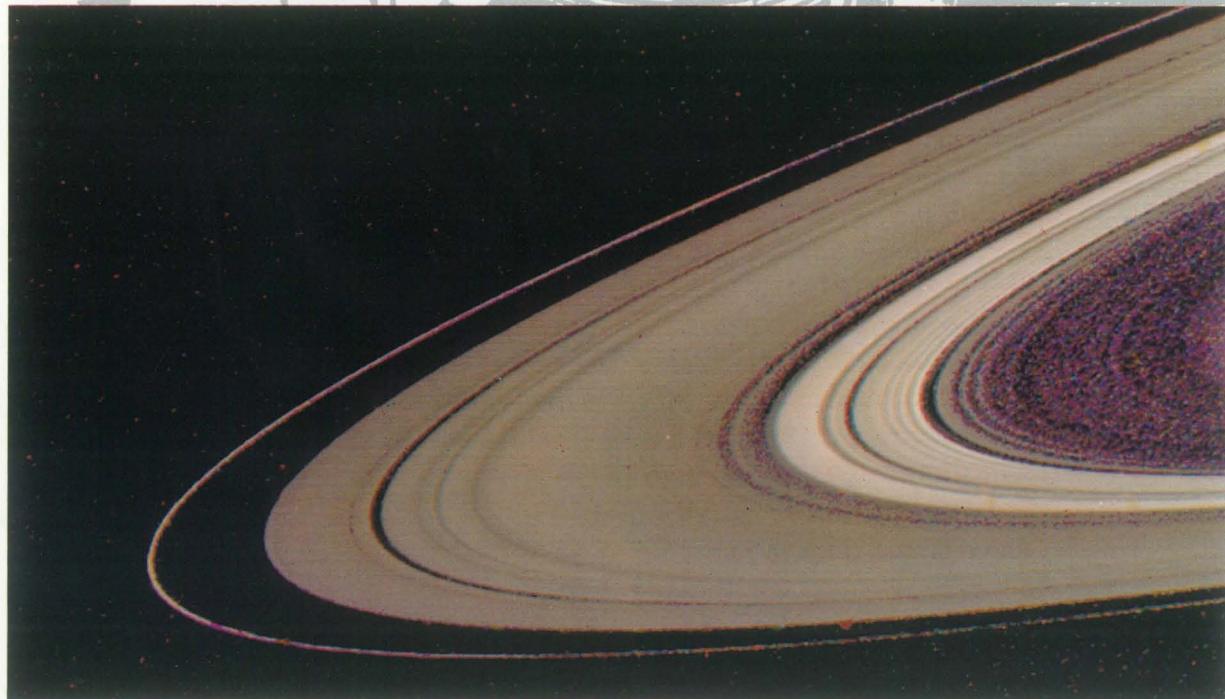
11/13/80 1.6 million km (930,000 mi)



***"Not fare well,
But fare forward, voyagers."***

T. S. ELIOT

◀ Rings of Saturn, with spokes, ringlets, gaps, and waves, hold clues to the origin and evolution of the solar system.



Saturn's rings show a wealth of detail to Voyager's cameras as the space-craft draws closer.

11/12/80 740,000 km (458,000 mi)

THE SECOND LOOK AT SATURN

Back on Earth, meanwhile, scientists pondered the same kinds of unexpected results they had encountered at Jupiter. So, in the few months that remained before Voyager 2's arrival at Saturn, the Voyager teams undertook to restructure a major portion of the encounter sequences for Voyager 2's 11 science instruments.

For this encounter, emphasis would shift from Saturn and Titan to the rings and to other satellites. The unexpected appearance of the rings dictated more time to their study, and detailed study of the satellites was a high-priority scientific objective.

The summer of 1981 began, and with it the encounter of Voyager 2 with Saturn. By now, profiting from their earlier experience, the scientists were able to set camera exposures at more exact levels, to cope with the low light levels and the general blandness of Saturn. On this approach Saturn presented alternating dark and bright bands of clouds and high-speed jet streams. Swirling cloud patterns, which were smaller versions of the large and intense storms seen on Jupiter, were also visible through Saturn's haze layer.

Voyager 2's cameras zeroed in on the rings, and scientists searched for small satellites in the rings that might cause the multiringed appearance. Those moonlets, some scientists believed, might sweep up material in the rings, creating gaps. Voyager 2 would soar closer to the rings, and the improved resolution of the pictures should show structure as small as one kilometer (0.6 mile) in diameter.

One of Voyager 2's most important experiments involved an instrument called a photopolarimeter, which measures light intensity. As Voyager 2 passed above Saturn, a distant star named Delta Scorpii appeared to move behind the rings. By measuring the starlight as it passed through the rings, the photopolarimeter detected changes in the starlight's intensity as it was altered by changes in the thickness of the rings.

Quick analysis of the data showed that the rings' structure was far different from what it appeared to be in the photos. No region was totally empty of ring particles. The members of the photopolarimeter team have 800,000 samples, each one a

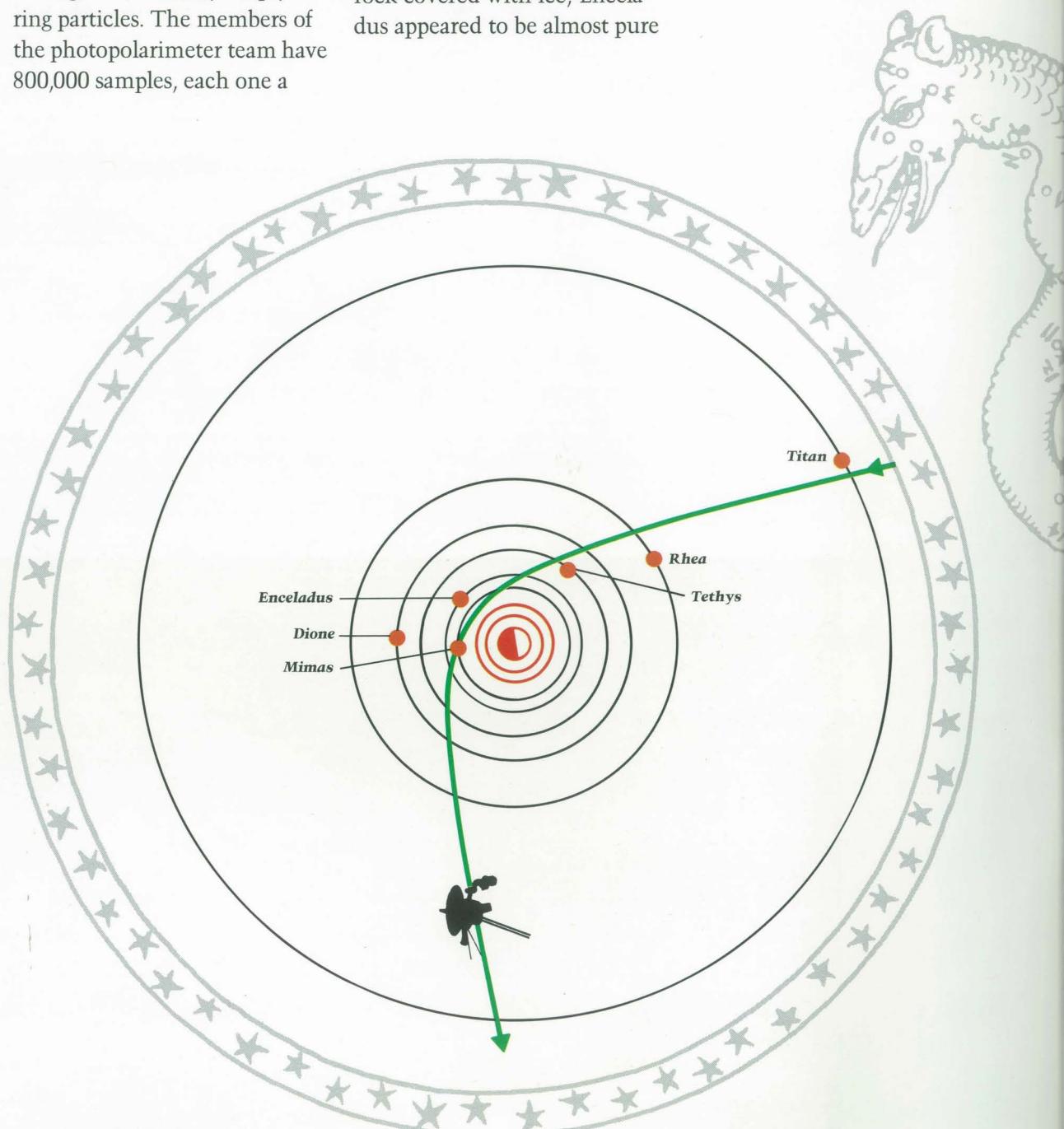
100-meter (330-foot) slice of the rings. It will take a decade to process and analyze the data.

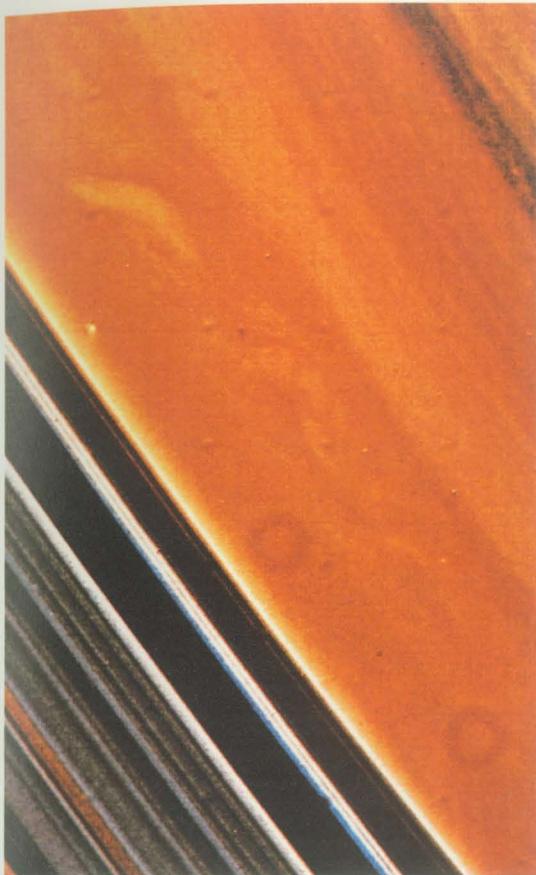
Voyager 2 photographed and measured all the satellites that were then known—their number had swelled to 17. At the end of the encounter, scientists had detailed data on all of them. Further study of Voyager pictures produced still more satellites, bringing the total to more than 20.

Saturn's satellites are different from those that orbit other planets. Some are composed of 30 to 40 percent rock covered with ice; Enceladus appeared to be almost pure

water ice, and is the most reflective body in the entire solar system. Iapetus, with one dark and one bright side, was a strange object that would require special analysis. Distant Phoebe, photographed several weeks after Voyager 2's closest approach to Saturn, was a maverick. It is almost certainly a captured asteroid, a relative newcomer to Saturn's fleet of celestial escorts.

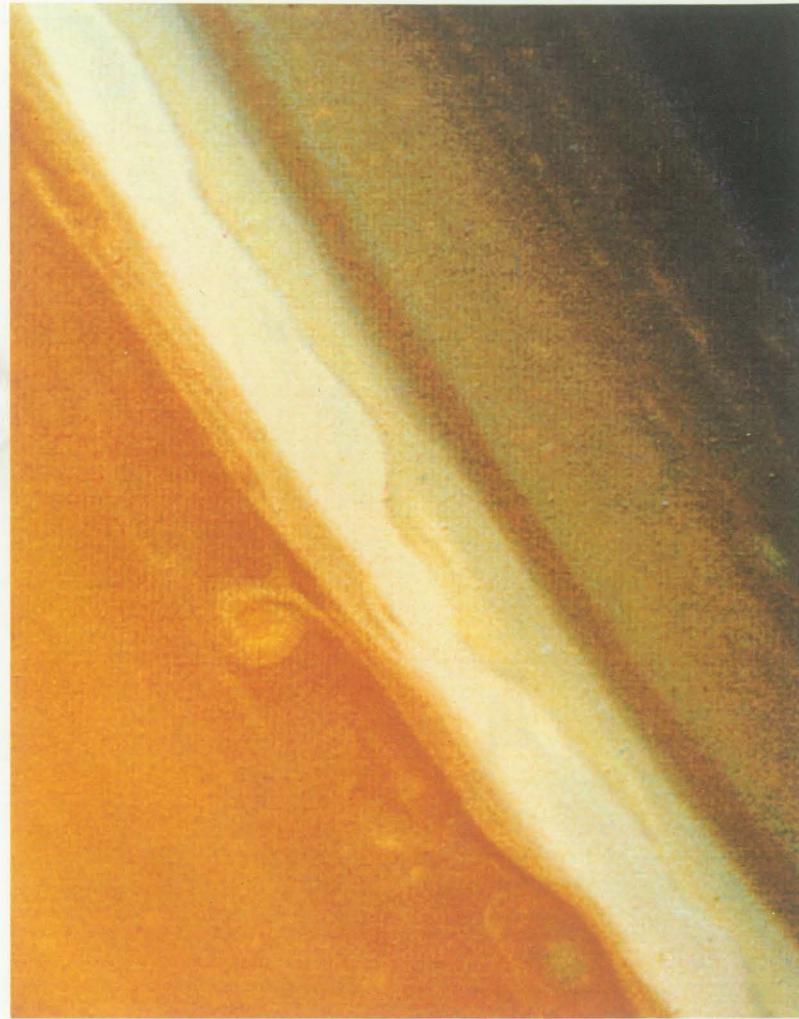
As Voyager 2 flew behind Saturn and out of the view of scientists and engineers back on Earth, a problem developed that





Huge storms and high-speed winds howl through Saturn's atmosphere. Winds were clocked by Voyager at 1,700 kilometers (1,100 miles) an hour.

8/20/81 6.5 million km (4 million mi)



8/16/81 9.3 million km (5.8 million mi)

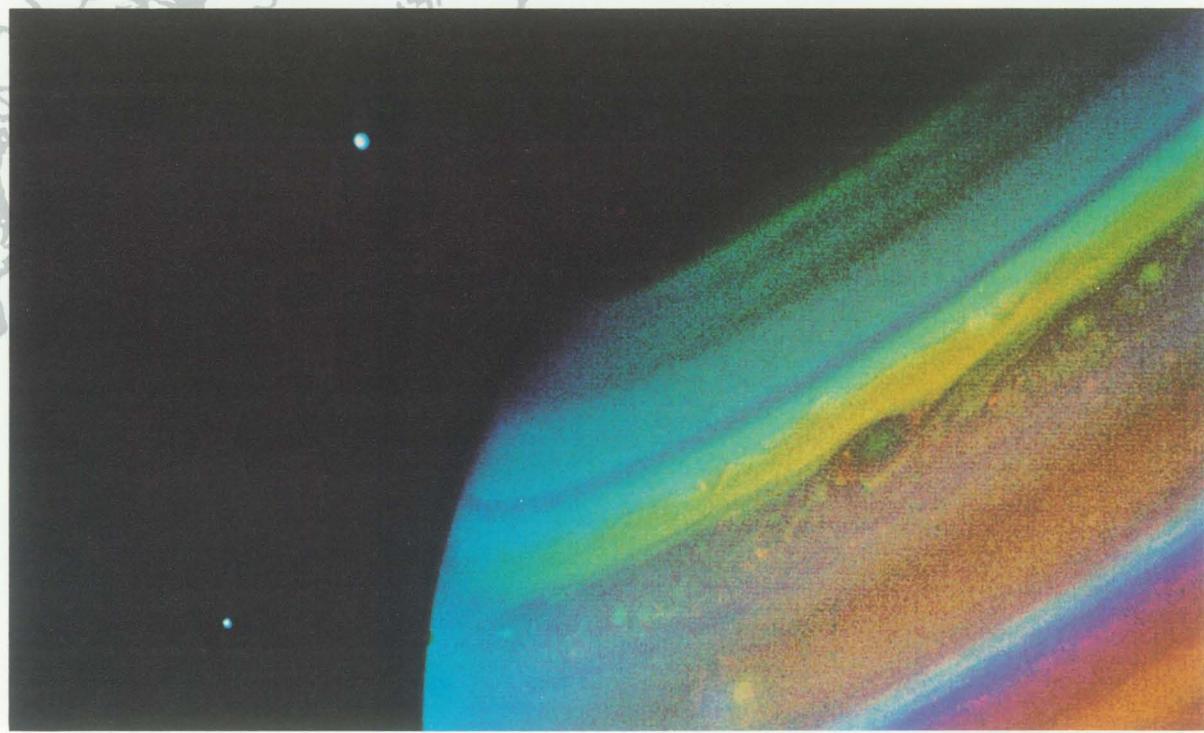
One huge storm, shaped like a great 6, swirls in Saturn's upper clouds. Just above the storm is a 530-kilometer- (330-mile-) per-hour jet stream.

***"I have seen starry archipelagoes! and islands
Whose raving skies are opened to the voyager..."***

ARTHUR RIMBAUD



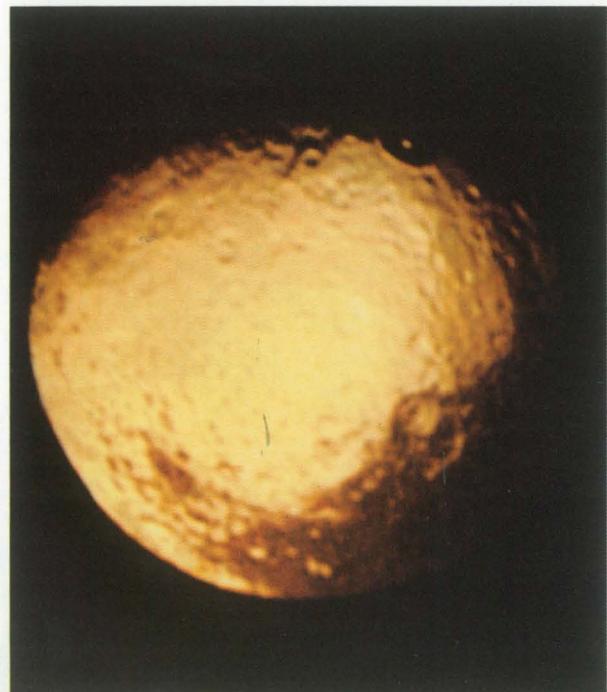
Two satellites orbit far above the storm clouds of Saturn in a false-color Voyager picture.



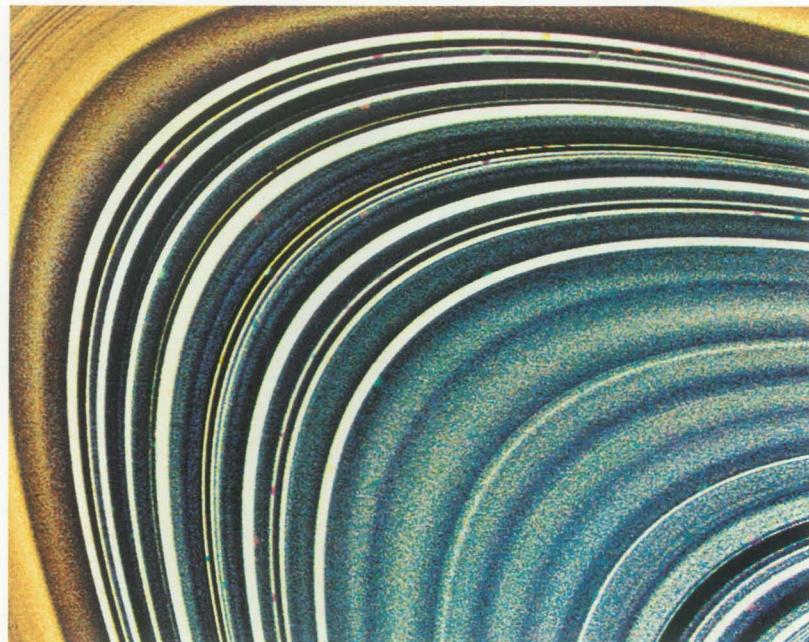
8/11/81 14.7 million km (9.1 million mi)

could endanger the remaining observations of this encounter and perhaps degrade the encounters with Uranus and Neptune years hence. While Voyager 2 was behind the planet, its scan platform, which carries its cameras and its infrared, ultraviolet, and photometric instruments, suddenly jammed in one direction of movement. The problem became apparent as soon as Voyager reappeared: Photos of black space appeared on the monitors at JPL.

Engineers on the project succeeded in moving the platform within a few days, to get important photos of Saturn and of Phoebe, the outermost of the satellites, then worked for weeks more with a duplicate scan platform at JPL to understand the problem. They determined that a worn shaft was the cause, but careful use of the platform should not prevent a successful Uranus encounter in January 1986.



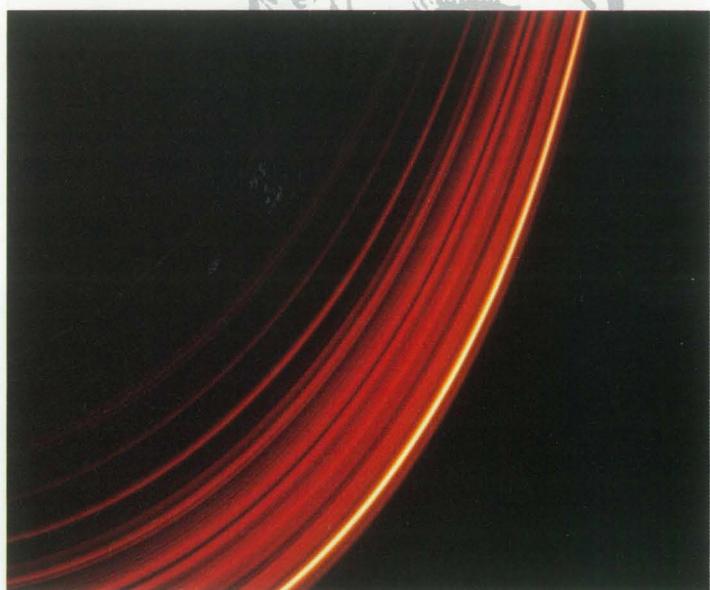
8/22/81 1.1 million km (680,000 mi)



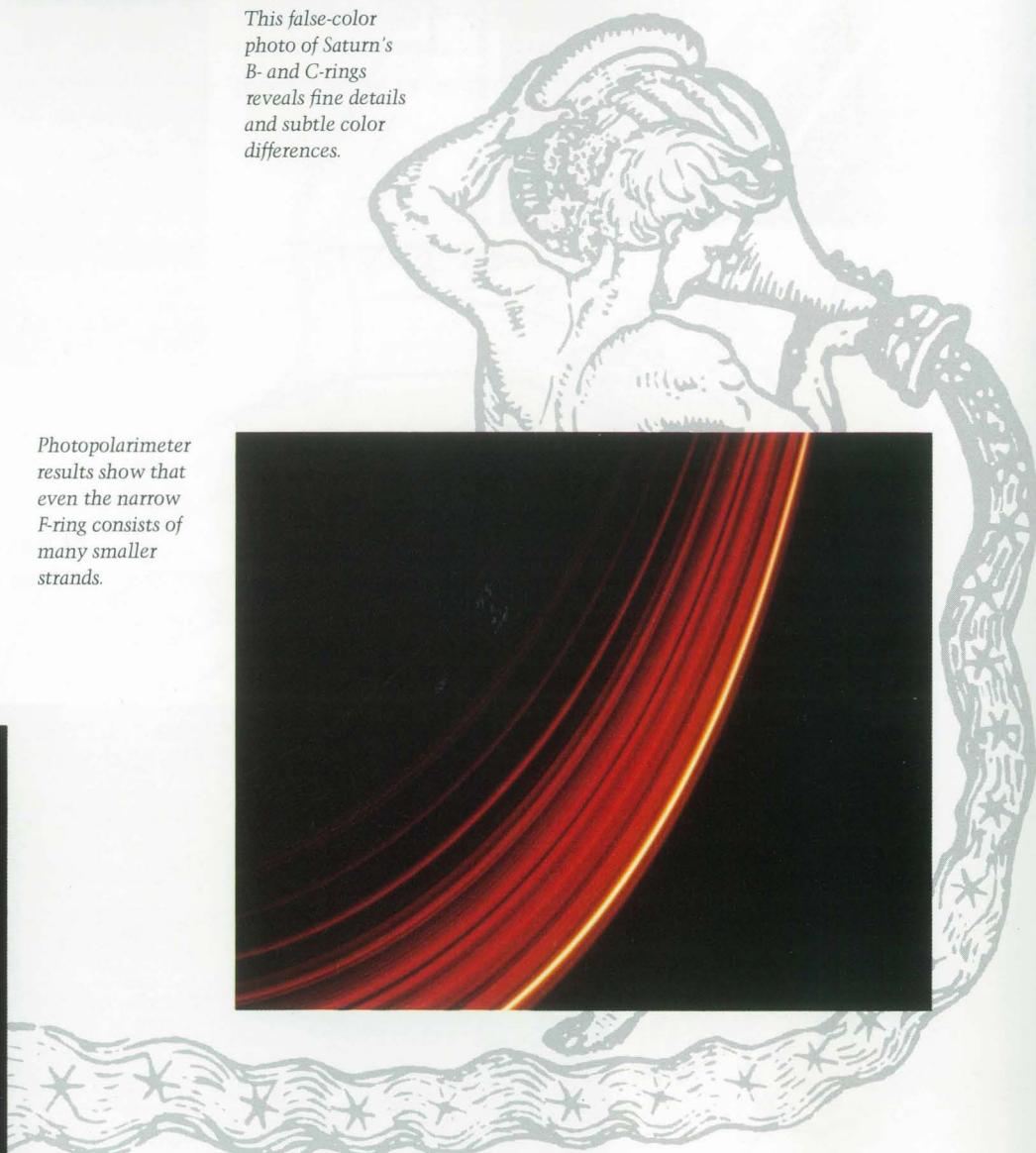
2.7 million km (1.7 million mi)
8/23/81

A departure photo shows Saturn in false color. The rings can just be seen, and their shadow falls across the planet.

This false-color photo of Saturn's B- and C-rings reveals fine details and subtle color differences.

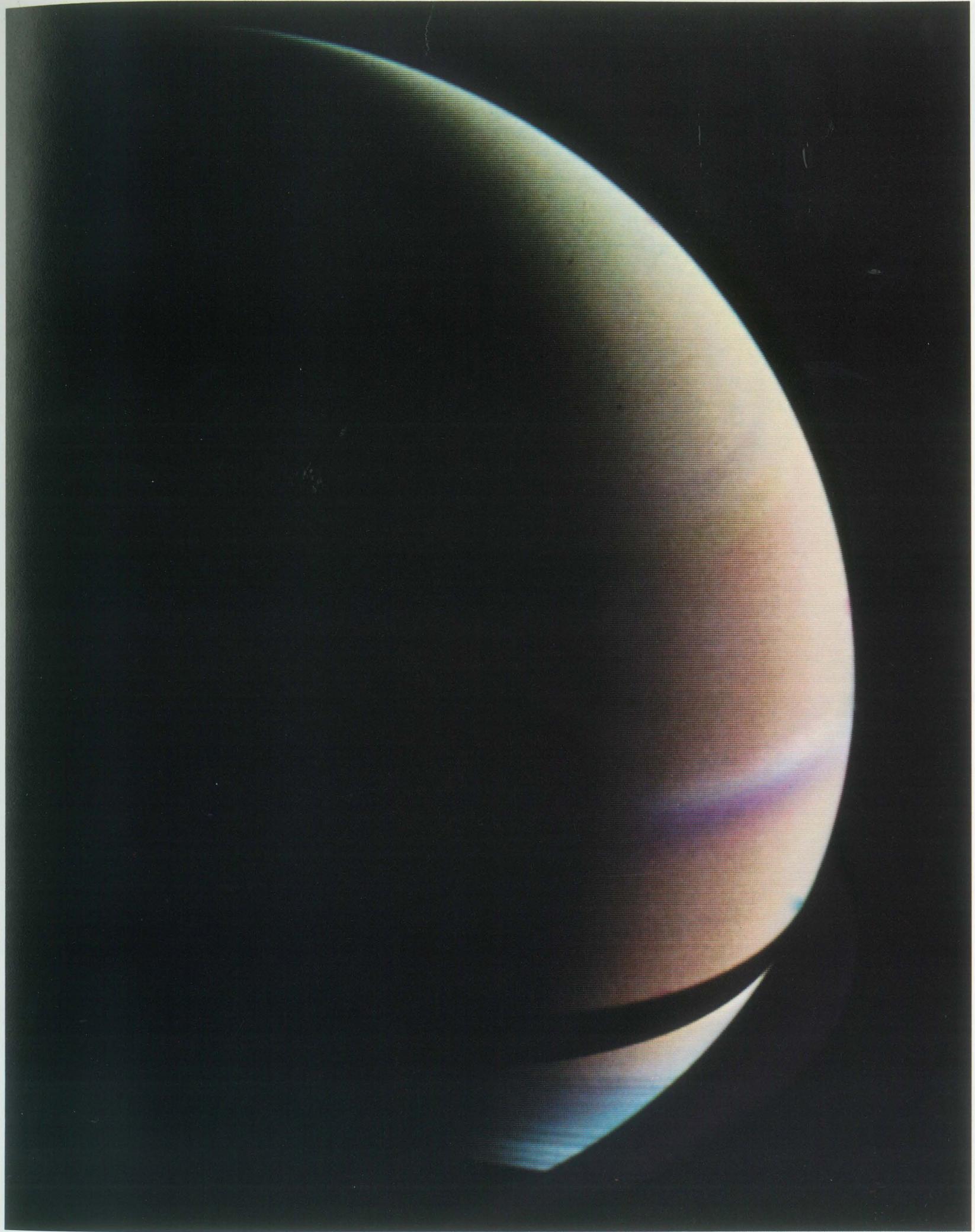


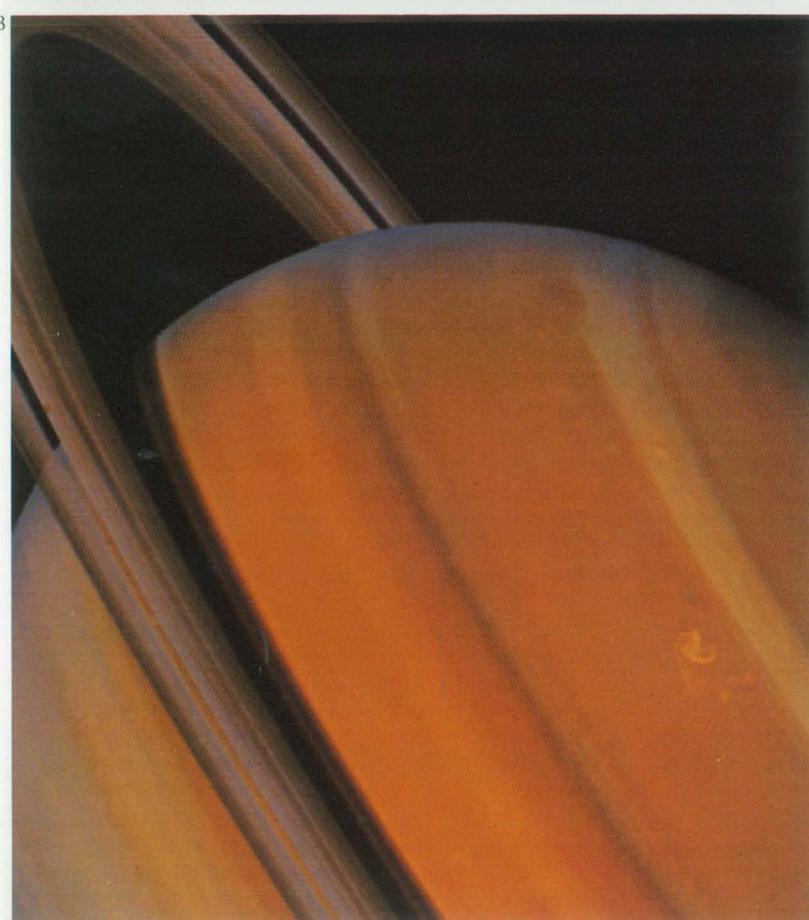
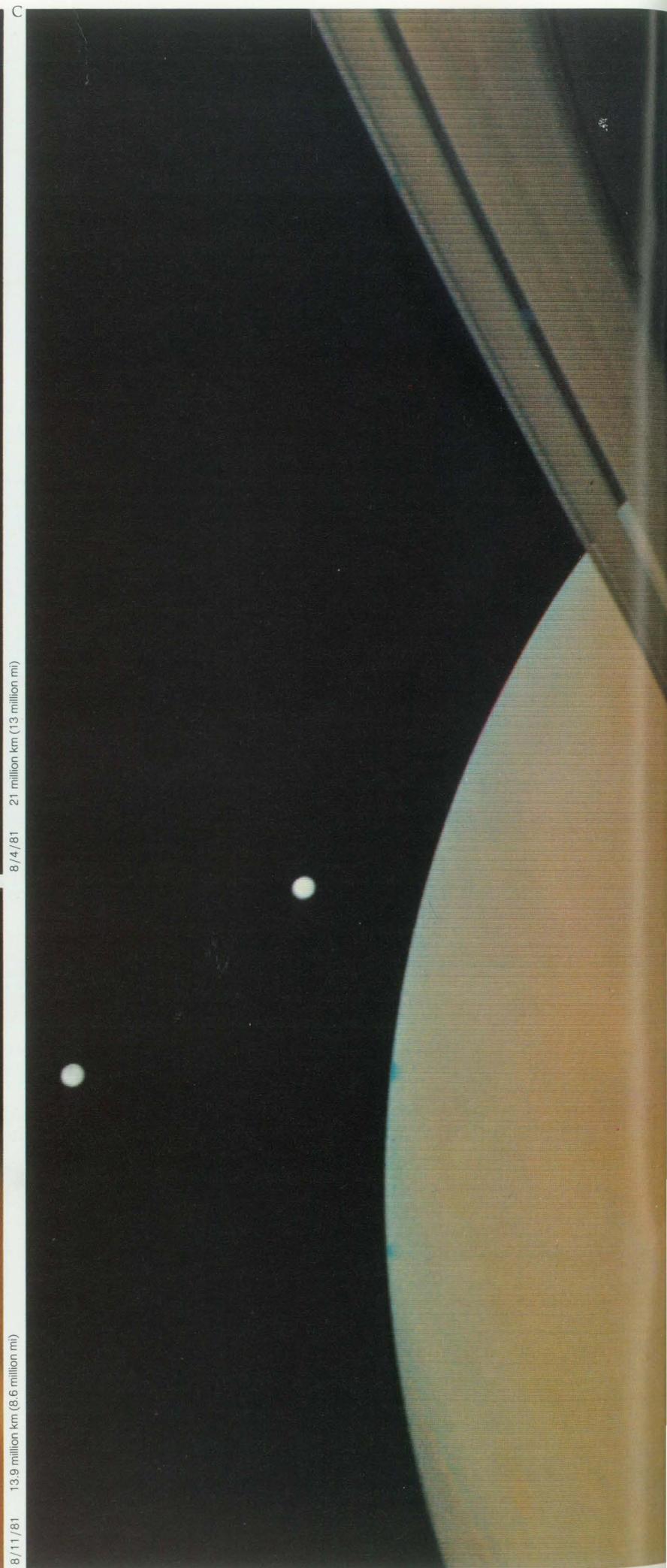
Photopolarimeter results show that even the narrow F-ring consists of many smaller strands.



**"It ended...
With his body changed to light,
A star that burns forever in that sky."**

AZTEC—THE FLIGHT OF QUETZALCOATL

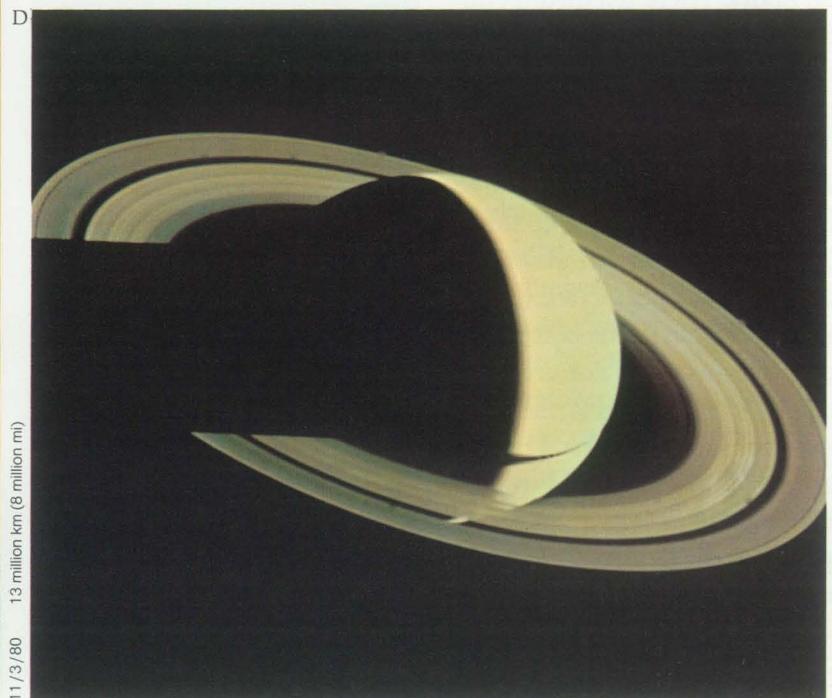


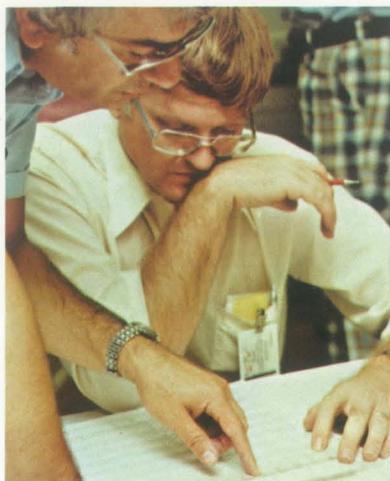


THE SATURN PICTURES

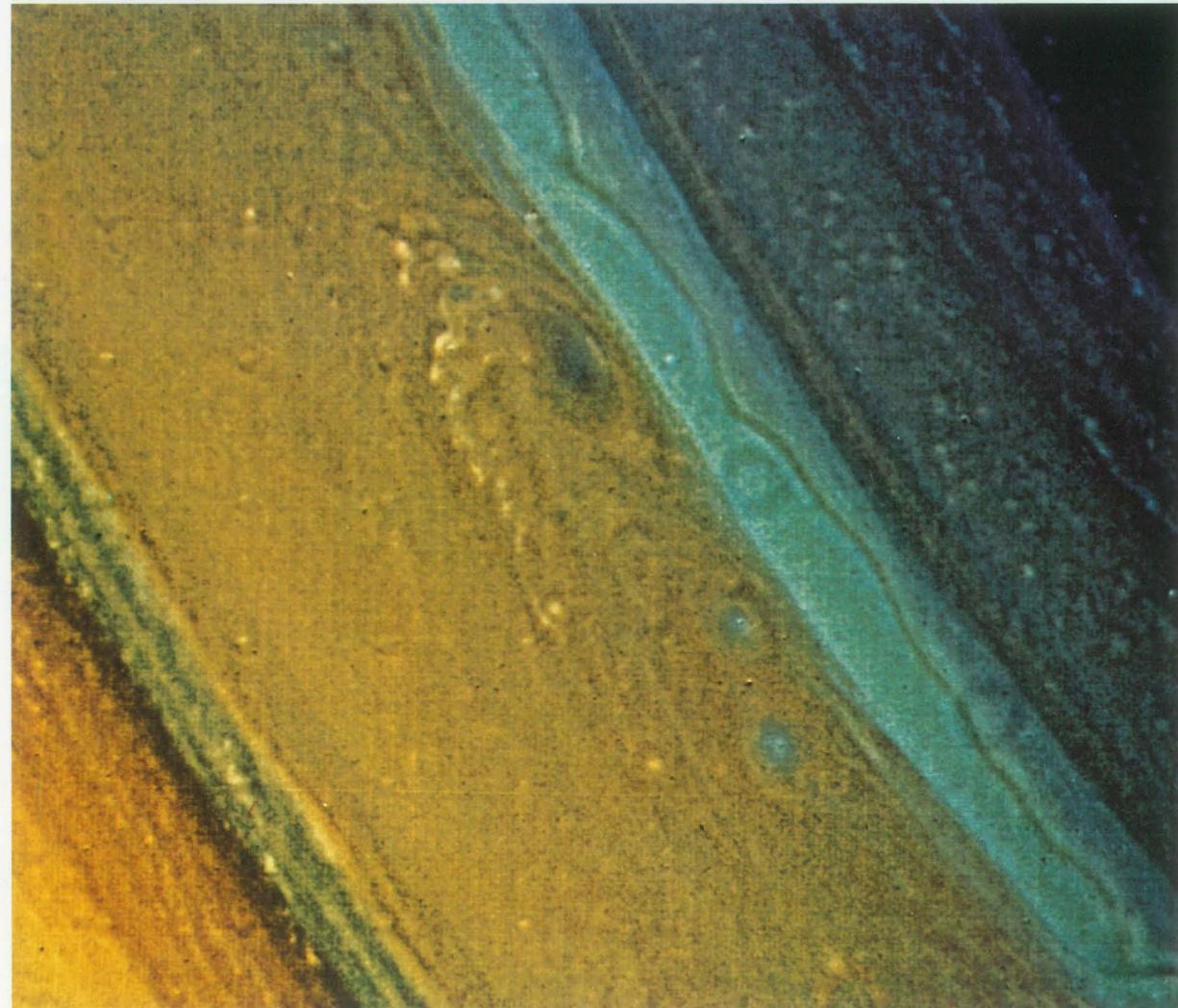
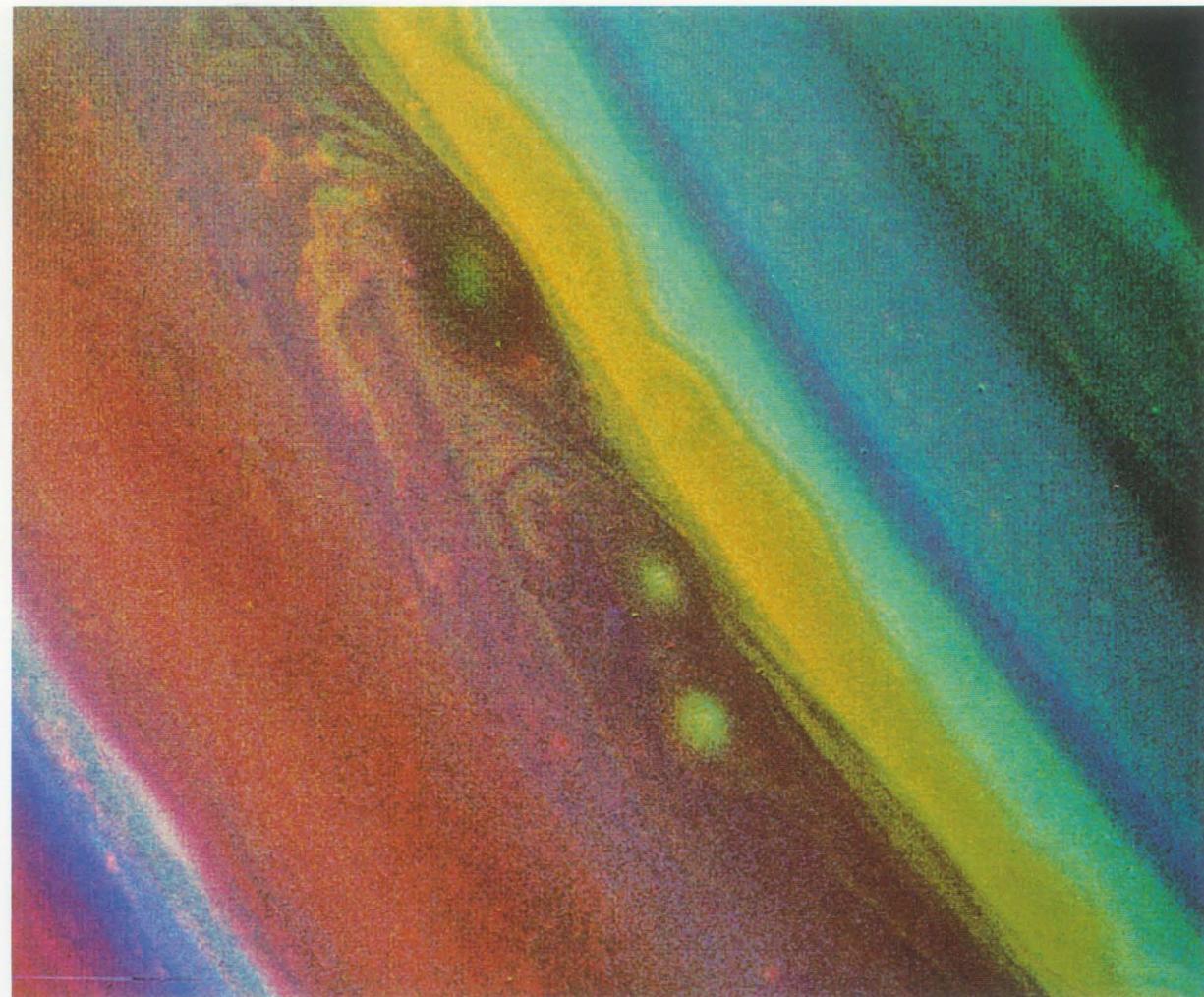
Saturn has been known for hundreds of years as "the ringed planet." Although generally similar to Jupiter, it has marked differences. Because it is twice as far from the Sun, Saturn is much colder than Jupiter—the amount of sunlight reaching it is only one-fourth of that reaching Jupiter. Saturn (A) has much less intrinsic color than Jupiter. One storm system, with bright, white clouds, is readily visible (B) just below a band of white clouds. Saturn is clearly visible through the wide gap in the rings called the Cassini Division. The blue color on the limb, which is artificially enhanced, is caused by the scattering of sunlight in the upper part of the atmosphere. Saturn would look like (A) to an observer aboard the spacecraft. The clouds we can see on Saturn are mostly frozen crystals of ammonia ice. The apparent difference seen here between the clouds in the northern and southern hemispheres may be a seasonal effect, since it is spring in Saturn's northern hemisphere. The wide gap in the rings separates the outer A-ring from the brighter

B-ring. The C- or crepe ring is visible (B) inside the B-ring. Three of Saturn's satellites (A) (top to bottom), Tethys, Dione, and Rhea, are visible. Tethys casts its shadow on Saturn's clouds. Spokelike features in the rings are at the extreme upper left. In the shadow cast by the rings (C) on the bland, almost featureless planet, sunlight can be seen streaming through the Cassini Division and another gap at the inner edge of the B-ring. The shadow cast by the C-ring is not as dark. Two icy satellites, Tethys and Dione, orbit the planet. As Voyager flew away from Saturn, its camera took (D), which shows the northern illuminated side of the rings; the spokes were darker than the rest of the rings during approach, but appear lighter here, indicating the spoke material is composed of fine grains that forward-scatter sunlight. The shadow of the planet falls on the rings, and the ring shadow on the planet. Saturn's bright crescent can be seen through the rings, indicating that the rings are optically relatively thin. The rings are thought to be composed primarily of water ice.

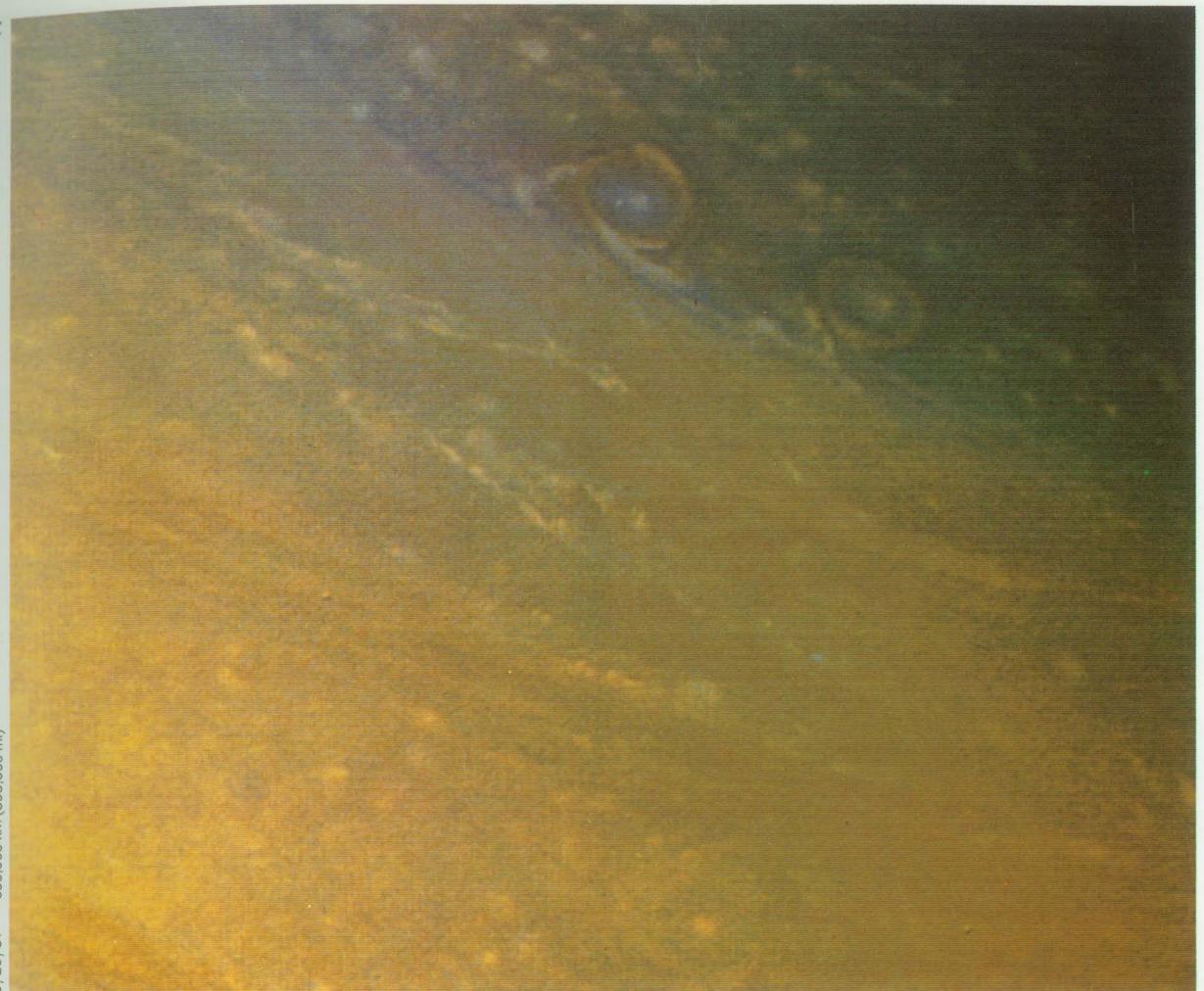




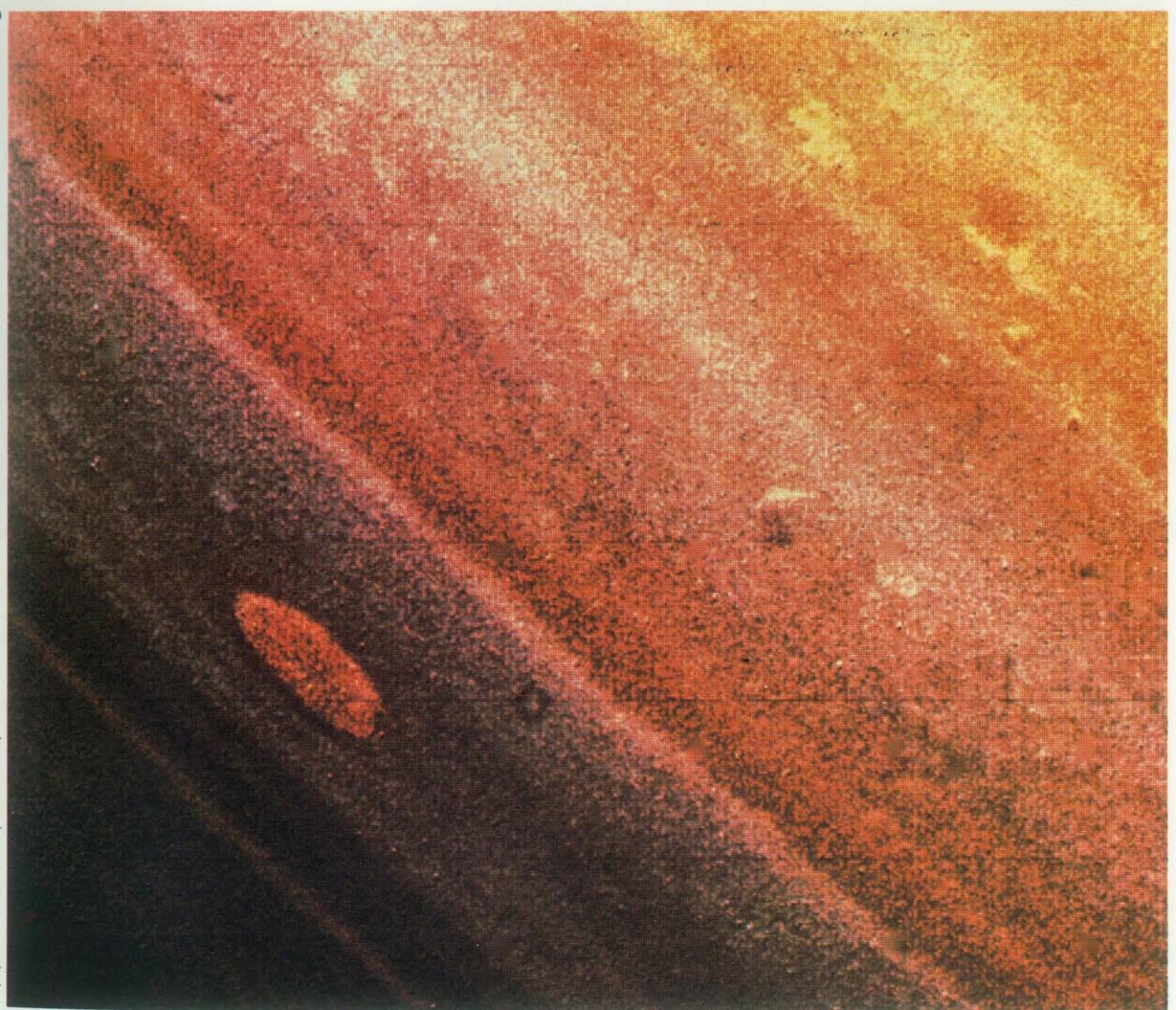
False-color imaging helps scientists see features that cannot be seen as well in true color. Green, violet, and ultraviolet filters were used to take (A), while (B) was taken in green and violet only. They are of the same region in Saturn's northern hemisphere, and show three large storms. The three storms would appear brown in normal color and are called "brown spots." Ultraviolet image (A) shows that the storms have centers brighter than surrounding regions, indicating a high-altitude haze layer above. The largest of the spots is about 5,000 kilometers (3,100 miles) on its long axis and has an anti-cyclonic (counterclockwise) motion that reaches speeds of 30 meters per second (67 miles an hour). There is a distinct difference in the hazes and clouds on opposite sides of the wavy jet stream above the three spots. There is also a large difference in atmospheric temperatures between the two opposite sides. The jet stream has winds of up to 160 meters per second (330 miles per hour). The bottom photo shows puffy convective clouds in the region farther north of the jet stream. They are generally organized into a chevronlike pattern (which points to the left) because of the different wind speeds.



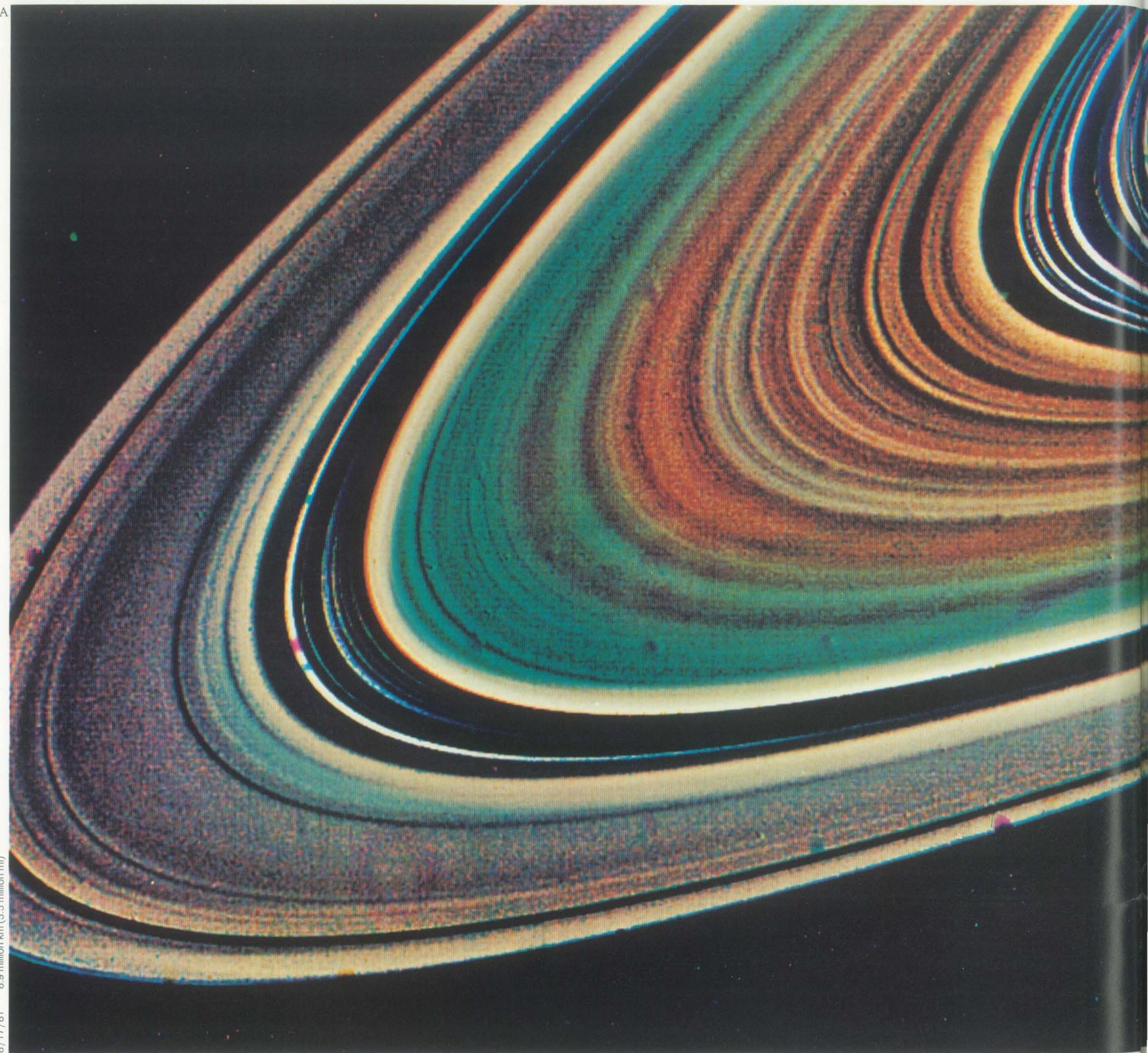
C



D



The northern and southern hemispheres of Saturn are seen in these two photos. A region near Saturn's north pole (C) shows three circular storms; two are near 72 degrees north latitude. Some scientists suggest that atmospheric circulation extends deep into Saturn, perhaps right down to the core and extending, from north to south, clear through to the other hemisphere. There are striking similarities between Saturn's northern and southern hemispheres. Eastward winds reach a maximum speed of almost 1,750 kilometers (1,100 miles) an hour near the equator, and fall off almost identically with increasing latitude, both north and south. A storm rages in Saturn's southern hemisphere (D), similar to Jupiter's Great Red Spot, but only 3,000 kilometers (1,850 miles) in diameter. Although its lifetime is not known, the storm was observed by both Voyagers, nine months apart. The source of energy for all the winds and storms on Saturn may be generated internally. Infrared measurements of atmospheric temperatures indicate that Saturn, like Jupiter, emits about twice as much energy as it absorbs from the Sun. However, in the case of Jupiter, the excess energy is believed to be a remnant of the high temperatures associated with its formation 4.6 billion years ago. Saturn, on the other hand, must have long since lost most of its original energy; it is possible that, at the lower temperatures of Saturn's interior, the helium separates from the hydrogen and sinks toward the center of the planet, releasing gravitational energy, which keeps the planet warm.

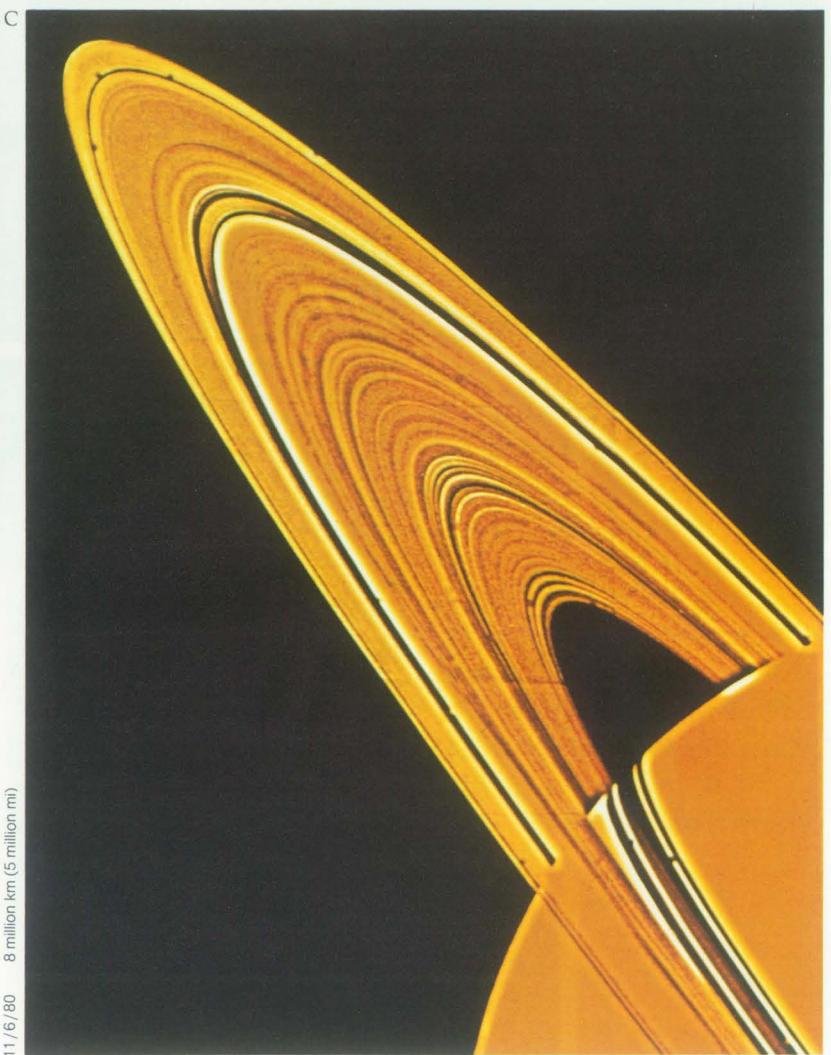
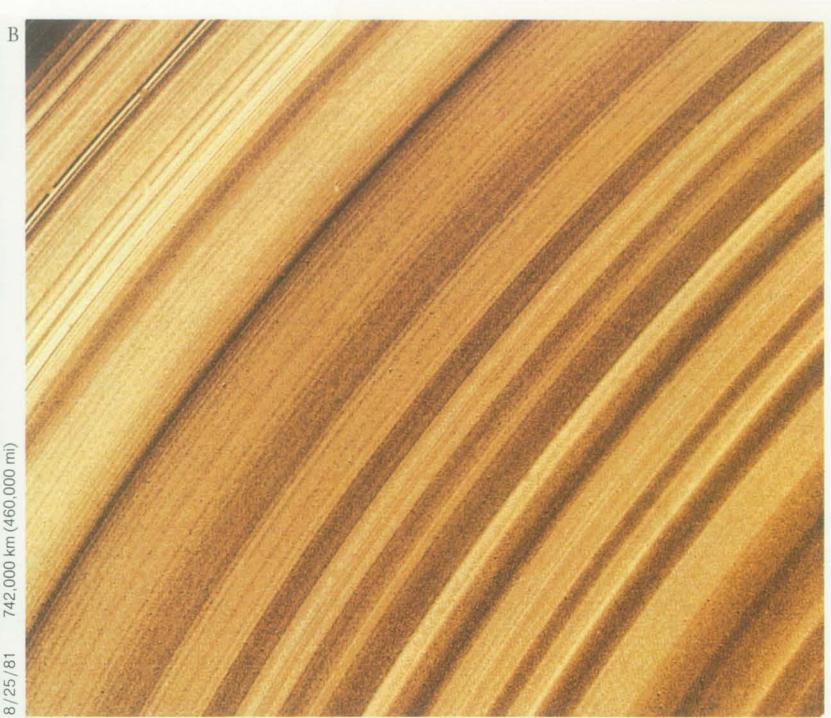
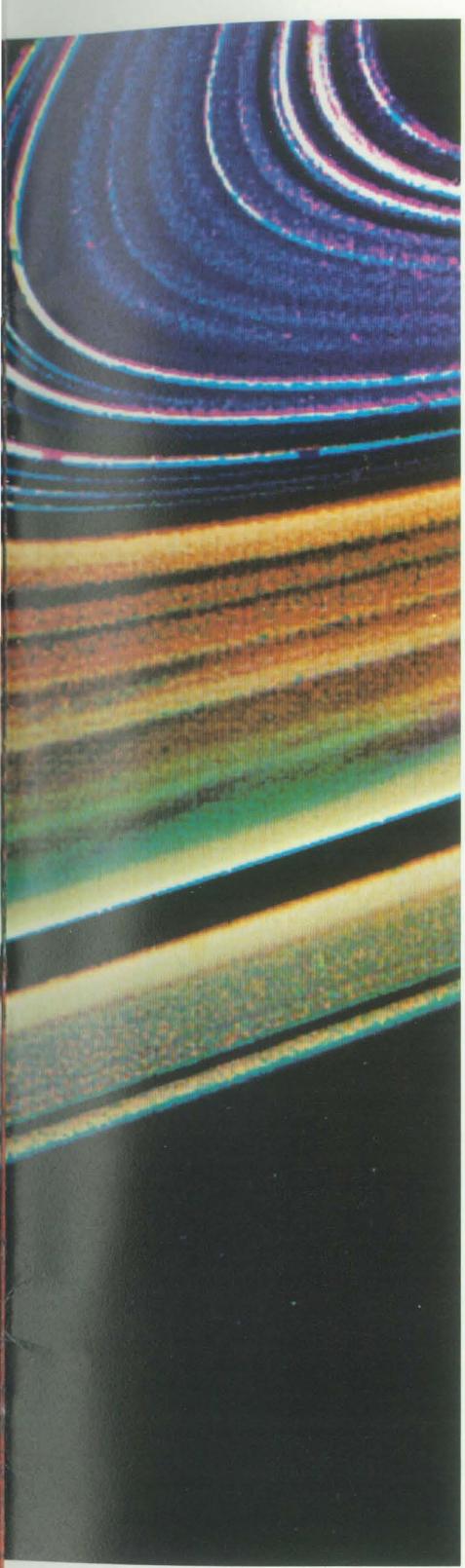


Saturn's three main rings exhibit very subtle color differences, which have been enhanced in (A). Although the main component of the rings is thought to be water ice, the color differences probably indicate slight differences in chemical composition and particle sizes. In particular, the Cassini Division and C-ring, which are more transparent than the A- and B-rings, are also

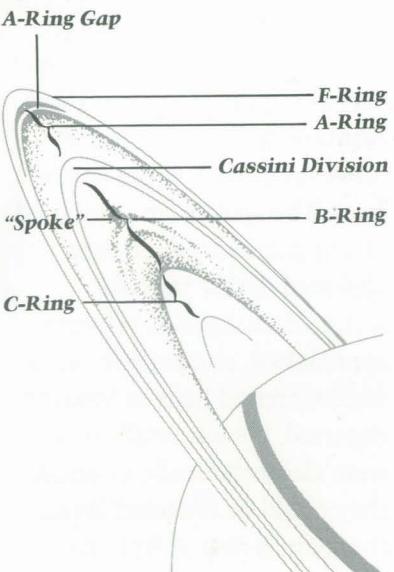
much less reflective in orange light. There are also large-scale color differences between the A-ring, which appears to be rather uniform, and the B-ring, which is highly structured, implying that mixing of material over geologic time is incomplete. Similarly, higher-resolution color photos of the

C-ring show surprising color differences between narrow adjacent ringlets. In particular, tiny eccentric ringlets found in the C-ring and the Cassini Division appear yellower in false-color images than adjacent ring material. From this distance, large features in the B-ring, at first believed to be individual ringlets, appear to have a scale of several hundred kilometers.

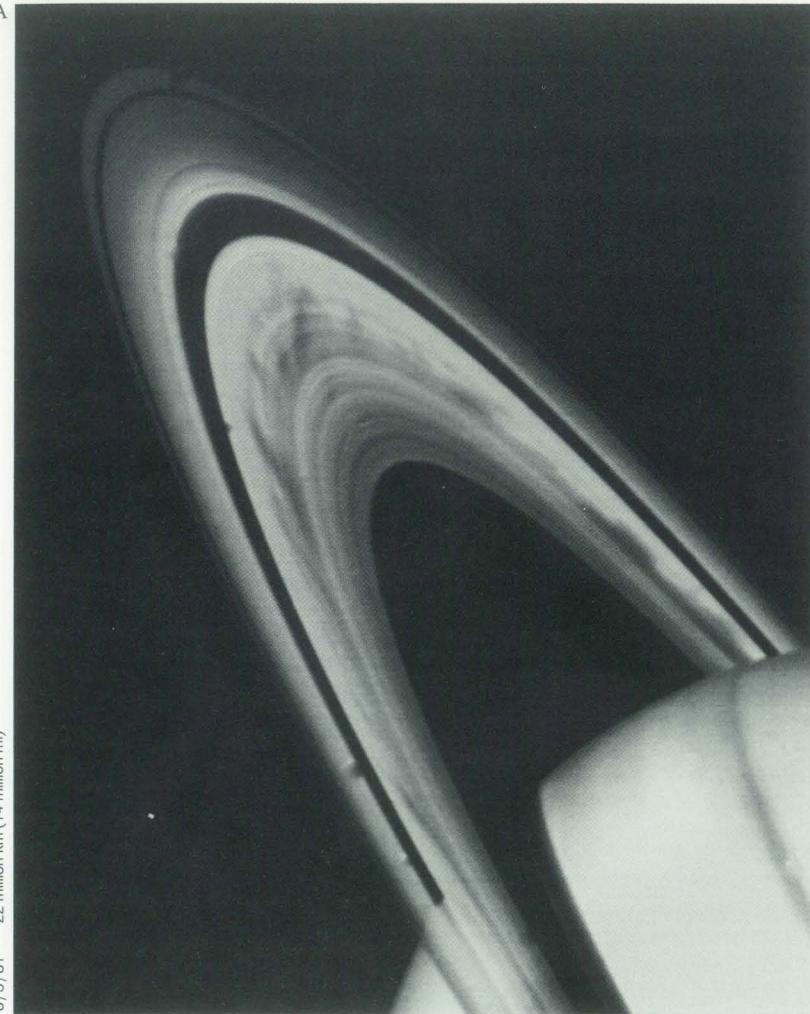
However, closer examination showed that there are no major gaps in the B-ring. The ring is continuous, and the "ringlets" are waves, most of which are set up by gravitational resonance with several nearby satellites.



The closer Voyager came to Saturn's rings, the more details appeared. What seemed to be ringlets, however, were later determined to be alternating areas of thicker and thinner material caused by gravitational effects from nearby satellites. The areas (B) in the outer B-ring are further divided by fine-scale structures that are 15-kilometer- (nine-mile-) wide wave features that move across the rings and are also caused by the gravitational interactions. The fine structures were found to be noncircular, as is the outer edge of the B-ring. Comparison of photos of the outer edge of the B-ring reveals it is elliptical, as would be expected from gravitational interaction with the satellite Mimas. Saturn is at the center of the ellipse, rather than at one focus. The difference in radial distance from the center of Saturn may be as great as 140 kilometers (87 miles). Special processing brings out radial structure (C) in the rings while ignoring differences in brightness. Thus the normally darker and more transparent C-ring and Cassini Division appear to be as bright as the normally brilliant A- and B-rings. (Dark spots are engraved on the camera's vidicon tube and are not ring features.)



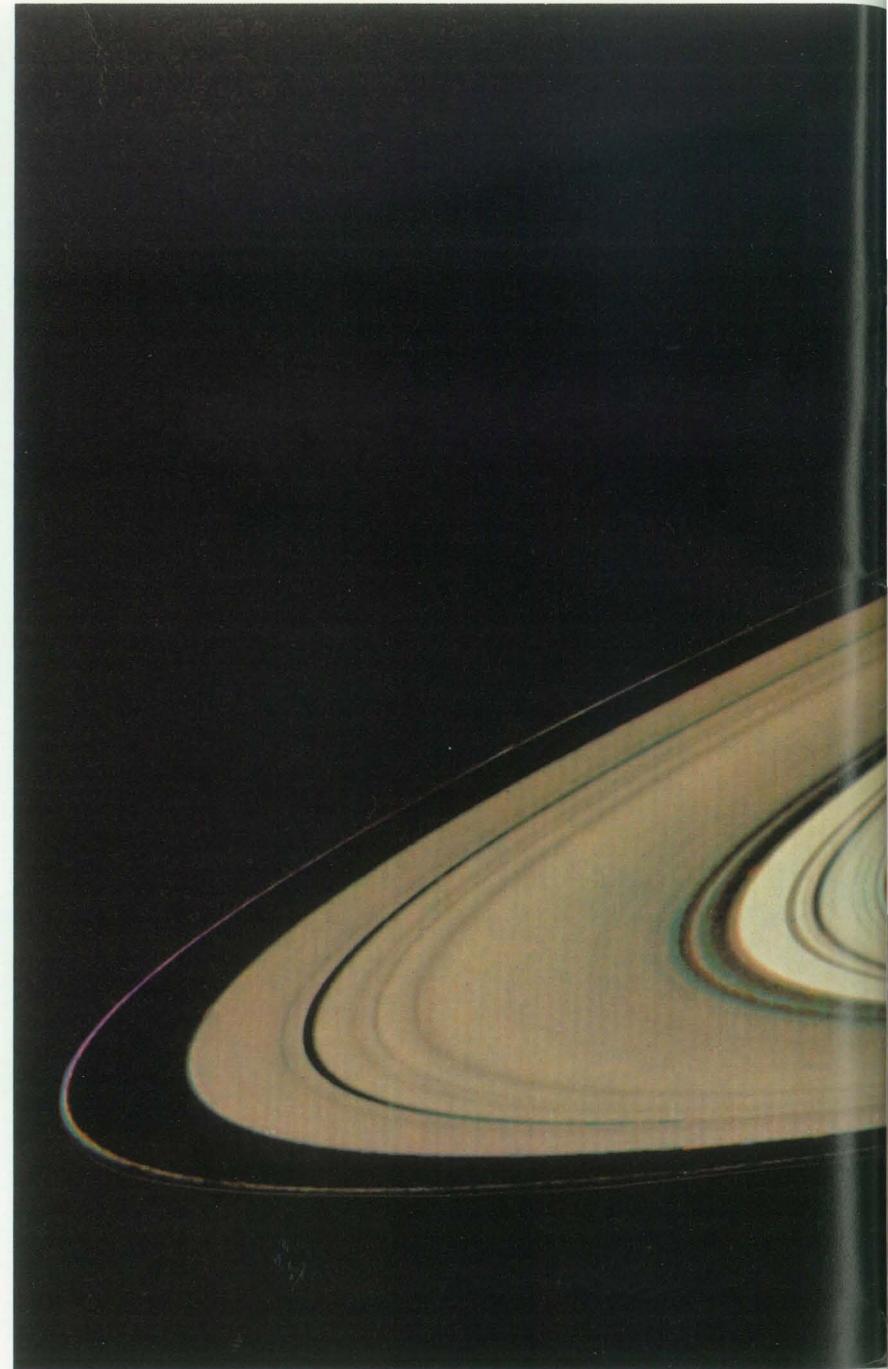
A



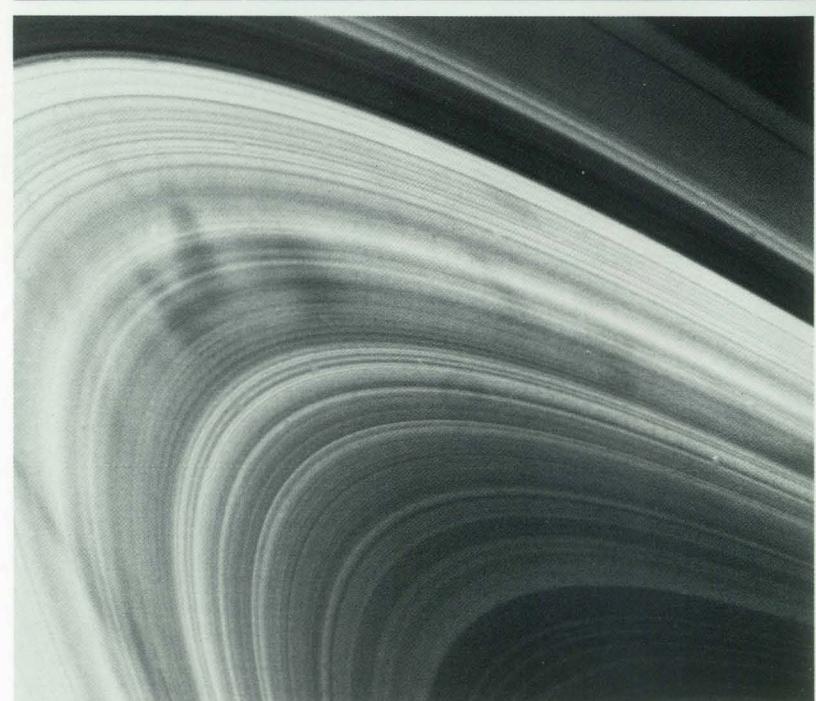
8/3/81 22 million km (14 million mi)

Radial features in the rings that initially reminded scientists of spokes on a wheel are apparent in the B-ring. Spoke features (A) are more apparent on the morning side of rings, so scientists speculate that their formation may be related to recent emergence of the ring material from Saturn's shadow. Spokes appear to form radially over a distance of 10,000 kilometers (6,200 miles), while older spokes are skewed because of their normal orbital motion that causes ring particles closer to the planet to move faster than those farther away. The spokes are composed of tiny particles, since they appeared darker in back-scattered sunlight as Voyager approached, and brighter in forward-scattered light as Voyager departed. If such small particles were electrostatically charged, they could be levitated above the main B-ring. A link may

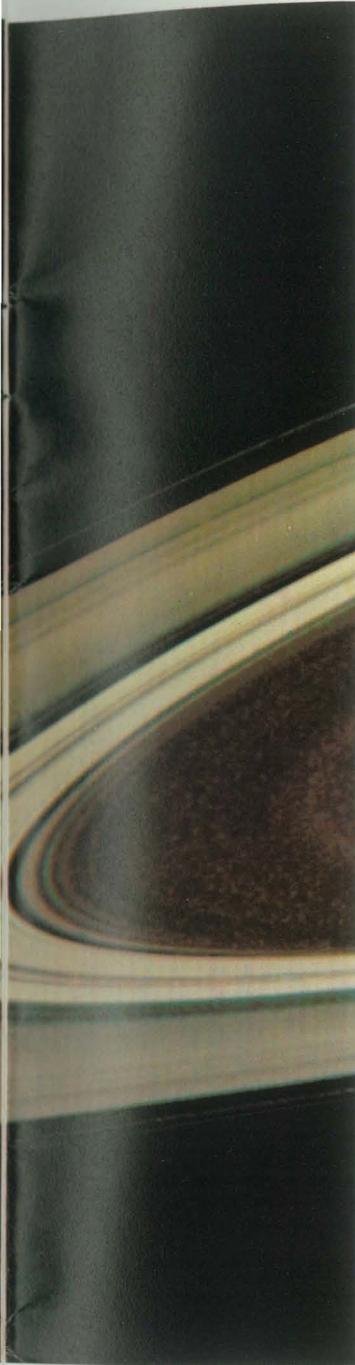
exist between spokes and electrostatic discharges observed by the planetary radio-astronomy experiment. If the discharges originate in the rings, as suspected, they might be linked either with formation or decay of the spokes. The spokes (B) are not continuous over bright portions of the rings, but are clearly seen against the darker areas.



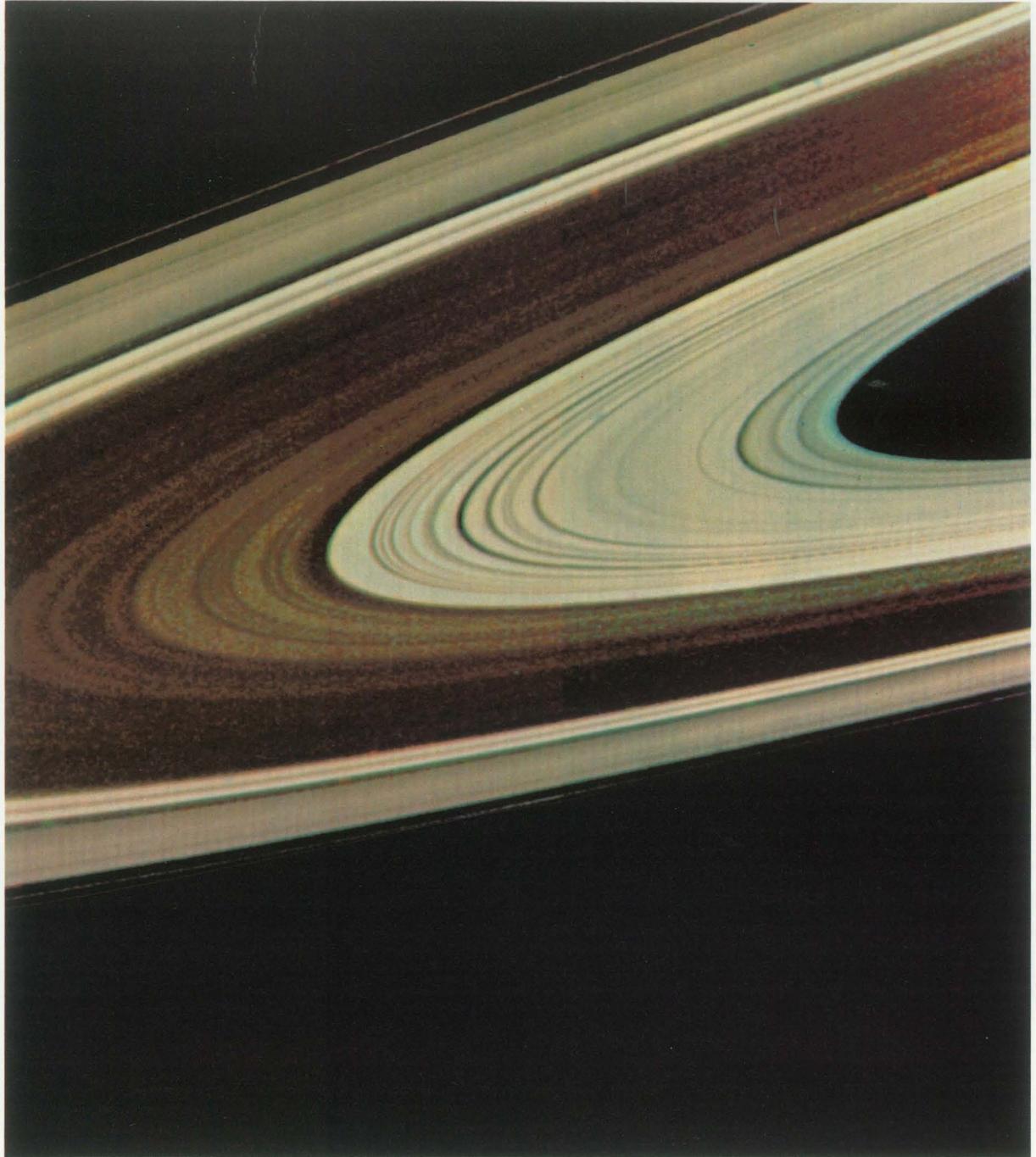
B



8/22/81 4 million km (2.5 million mi)



C



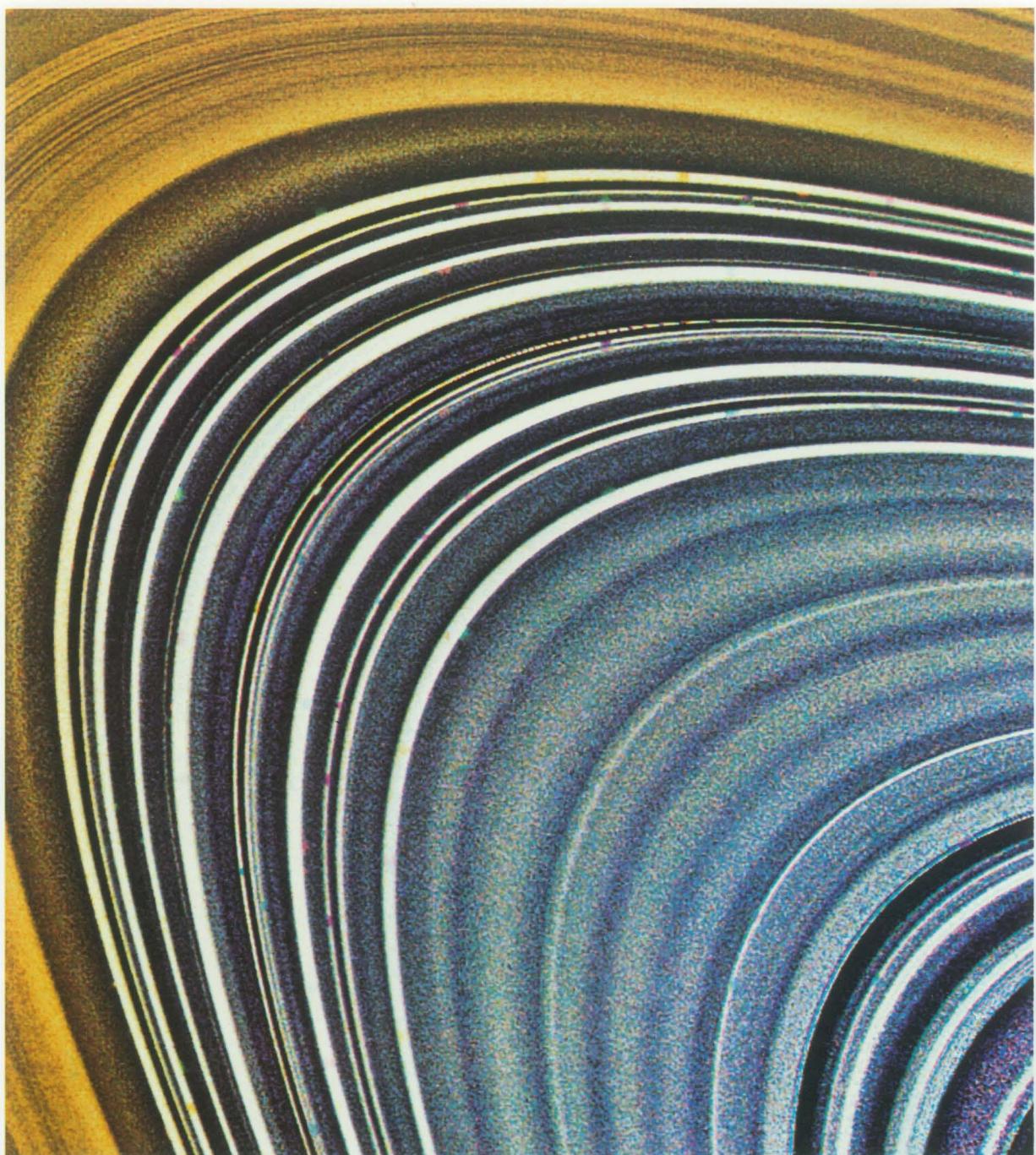
D

Saturn's rings appear dramatically different when viewed from the unilluminated side (C and D), when the sun is shining on the opposite face. The more transparent C-ring and Cassini Division are bright, because the sunlight can penetrate them, while the normally brighter B-ring, which is much denser, is quite dark. Thus the rings' brightness in these photos indicates the amount of sunlight transmitted through them. It is apparent that the inner half of the B-ring transmits more light, and is therefore optically thinner, than the outer half. A large popula-

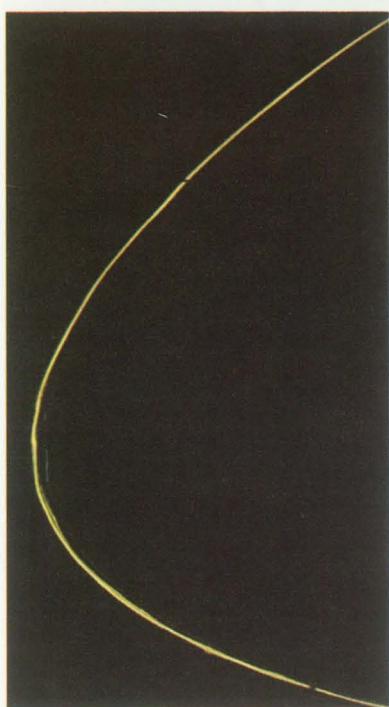
tion of fine material in the B-ring absorbs blue light, resulting in a reddish hue on its underside. A similar phenomenon on Earth is a sunset, where high-altitude, fine dust particles absorb blue light and give the sky its red color. The narrow, outer F-ring, discovered in 1979 by Pioneer 11, lies just outside the A-ring and is comparatively brighter when viewed from the underside. Comparison of

underside and topside photos of rings greatly aids in the analysis of ring thicknesses and particle sizes.

The changing geometry along Voyager's flight path provided a variety of striking views of the rings. The C-ring and inner B-ring (A) show subtle differences in false color. Large apparent color differences between the C- and B-rings, as well as slight differences within the C-ring, probably indicate particle-size differences or slight chemical-composition differences. The striking photo (B) shows the F-ring composed of three strands; two appear braided. The braiding is thought to occur in local areas of the F-ring when the inner of the two small shepherding satellites, which is in an eccentric orbit, comes closest to the ring material. The braids are constantly changing, since the satellites and the ring are constantly moving relative to each other. Just as Voyager 2 swept across the ring plane, the camera captured this oblique view (C) of the rings, in which several spokes appear as bright, horizontal streaks above the darker B-ring.

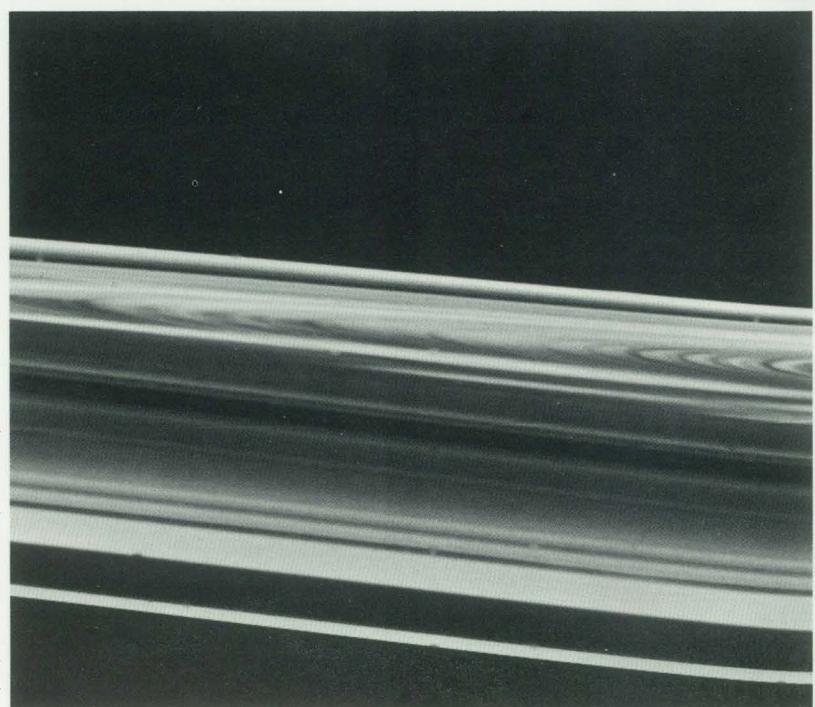


A



B

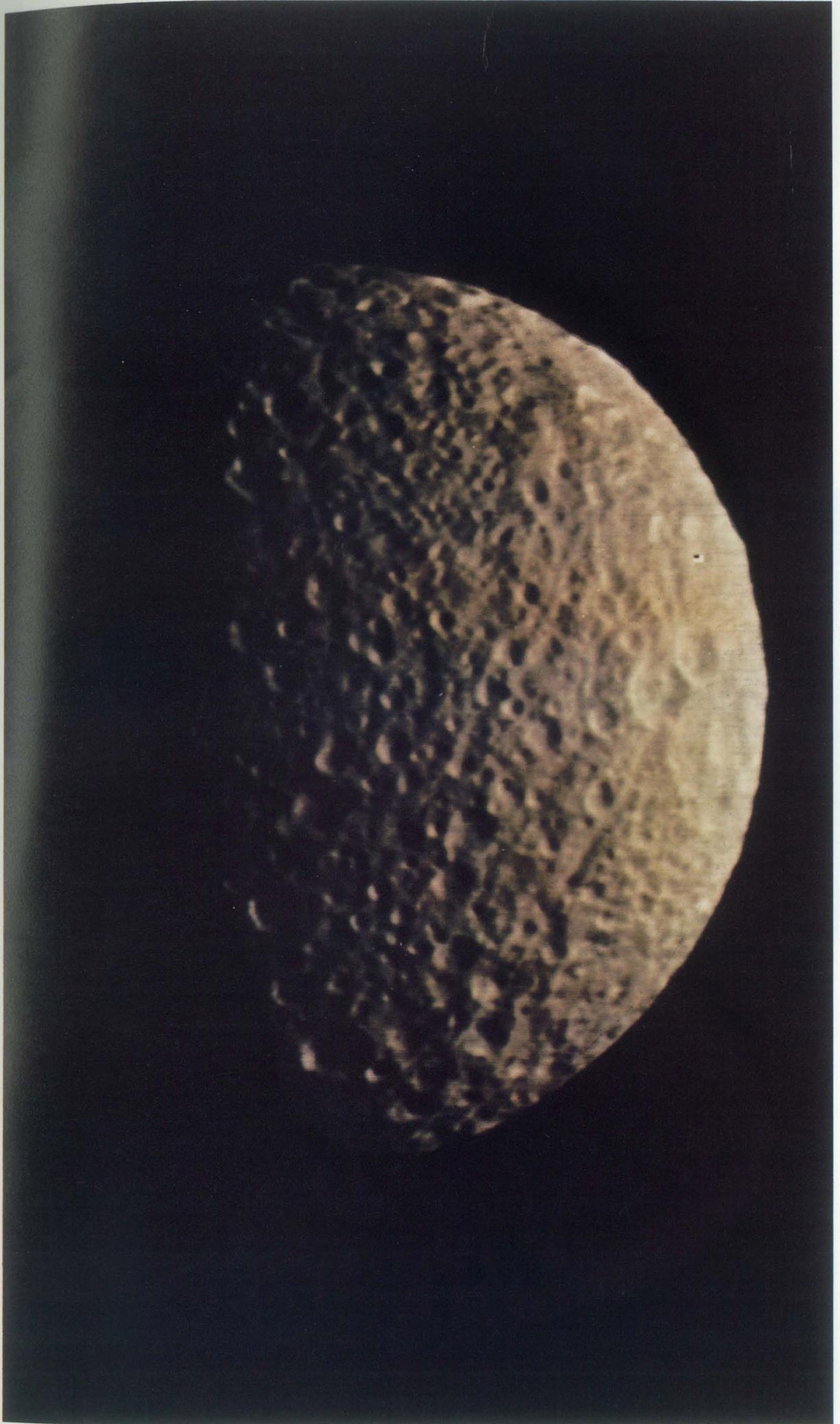
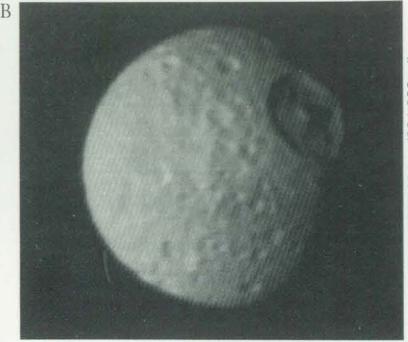
11/12/80 758,000 km (470,000 mi)



C

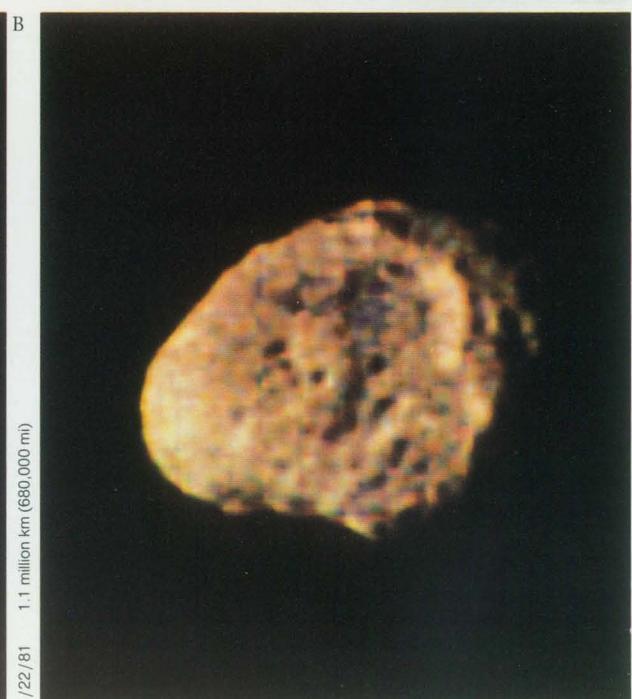
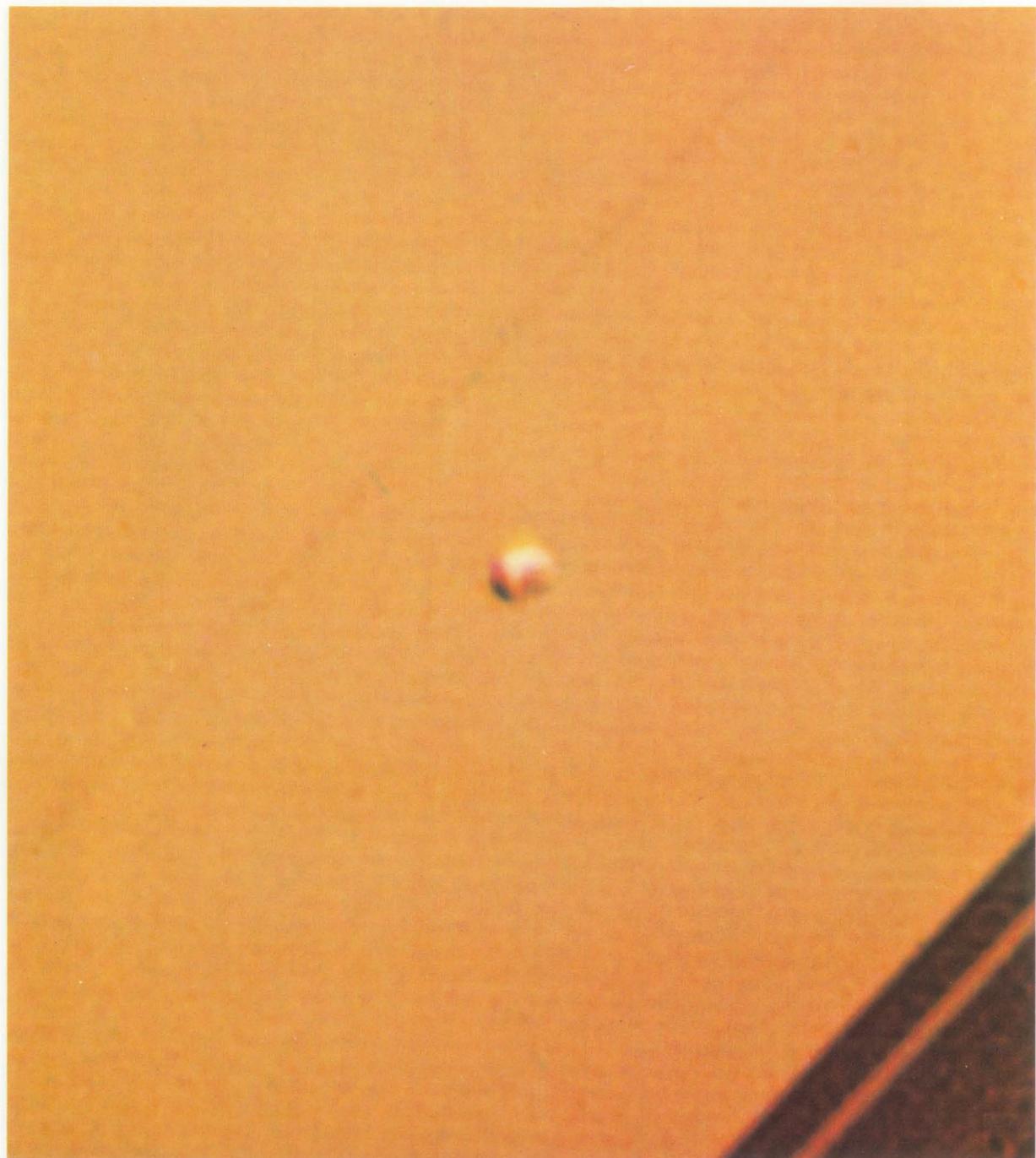
8/26/81 103,000 km (64,000 mi)

8/23/81 2.7 million km (1.7 million mi)

129,000 km (80,000 mi)
11/12/80425,000 km (264,000 mi)
11/12/80

Mimas, one of Saturn's icy satellites, revealed a huge crater (B), nearly centered on the leading hemisphere. The crater is so large, about 130 kilometers (81 miles) in diameter, that had the impact that caused it been much larger, it could have split the 392-kilometer- (244-mile-) diameter satellite apart. The central icy peak of the crater rises almost 10 kilometers (6.2 miles) above the floor, higher than Mount Everest. The south polar region of Mimas (A) records the history of heavy meteoritic bombardment. The density of small craters on Mimas is about the same as that for the uplands of the Moon. Evidence of surface fracturing is apparent in several deep canyons that wander across the face. It is possible the markings originated at the time of the crater-causing impact. Mimas, like most of Saturn's satellites, is believed to be composed mainly of water ice, and to contain between 20 percent and 50 percent rock.

Saturn's satellites exhibit a wide variety of sizes and shapes. Satellite 1980S26, the outer F-ring shepherd (A), is 110 by 90 by 70 kilometers (68 by 56 by 43 miles). The F-ring can be seen near it, the faint line just above and to the left of the satellite. The shadow of the rings is in the lower right corner. Iapetus (B) is the second-most-remote Saturnian satellite. Scientists knew Iapetus has one dark and one bright hemisphere, but Voyager provided the first detailed photographs of its surface. Dark material in this north-polar view reflects less than 5 percent of the sunlight striking it. The brighter portion reflects about 50 percent. Dark material is centered on Iapetus' leading hemisphere. That led some scientists to suggest that the dark material, perhaps from Phoebe, was swept out of orbit. The presence of dark material in the floors of some craters on the trailing hemisphere, however, leads others to prefer a model where the dark material comes up from Iapetus' interior. Since Iapetus is only 15 percent denser than water, it could contain low-density, carbon-bearing matter such as methane, which could give rise to the darker material. Its diameter is 1,460 kilometers (907 miles). Hyperion (C), one of the most battered bodies ever seen, is 410 by 260 by 220 kilometers (254 by 162 by 137 miles), probably the remains of a larger satellite that was destroyed by collision. Hyperion is relatively dark, reflecting only about 30 percent of the sunlight. If Hyperion is an icy body, then its dark color might be the result of contamination by material from elsewhere, as has been suggested for Iapetus.



A

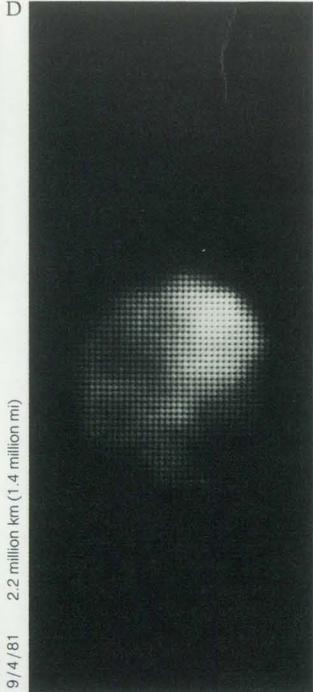
8/25/81 1.2 million km (750,000 mi)

C

500,000 km (300,000 mi)

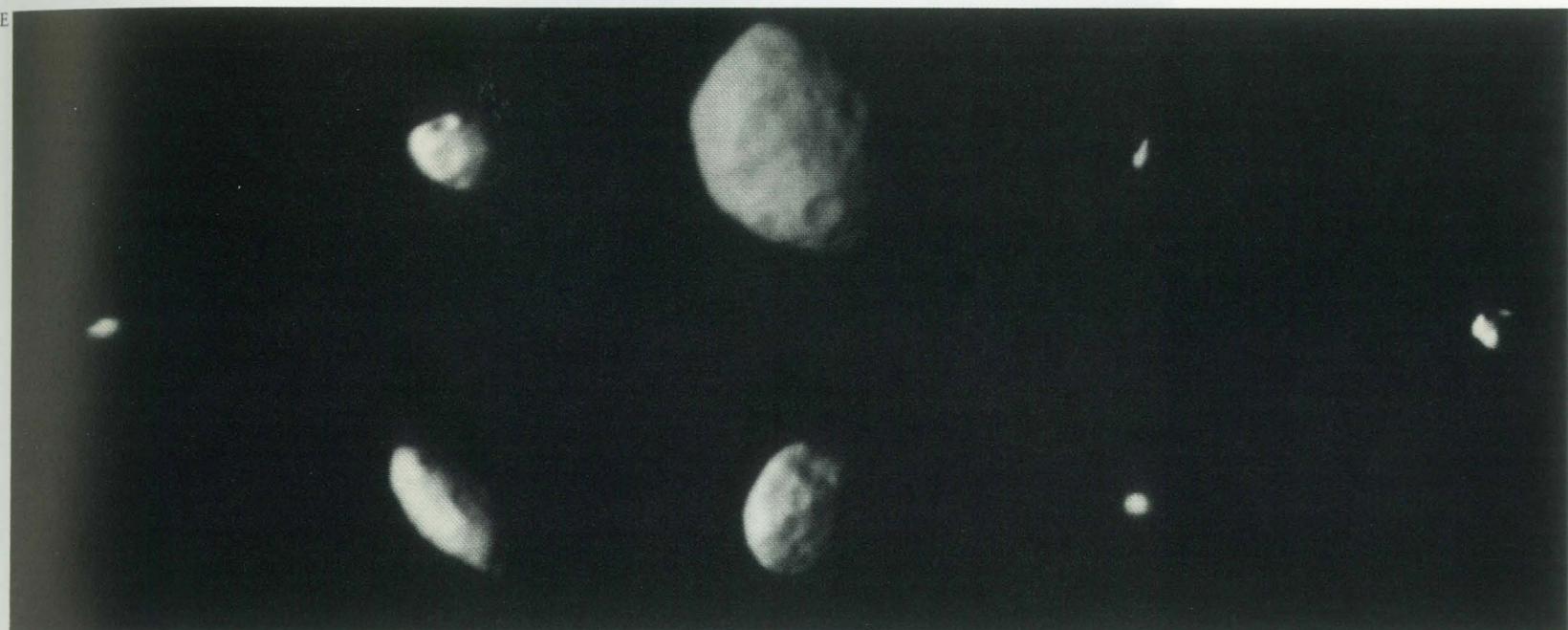
8/24/81

8/22/81 1.1 million km (680,000 mi)



Phoebe (D), outermost of Saturn's satellites, moves in a retrograde orbit almost 13 million kilometers away, more than three times as far from Saturn as Iapetus, its nearest neighbor. Phoebe is spherical (the photo was greatly enhanced) and is the darkest Saturnian satellite. Unlike all others, the 220-kilometer- (137-mile-) diameter object orbits Saturn in the ecliptic plane, rather than in Saturn's equatorial plane. Phoebe is the only Saturnian satellite that is known not to keep the same face always toward Saturn. It rotates in about nine hours and orbits

Saturn in about 550 days. Like the irregular outer satellites of Jupiter, it is thought to be a captured asteroid, rather than an ice ball that formed near Saturn. If it is an asteroid, Voyager's photos are the first ever taken of such an object.

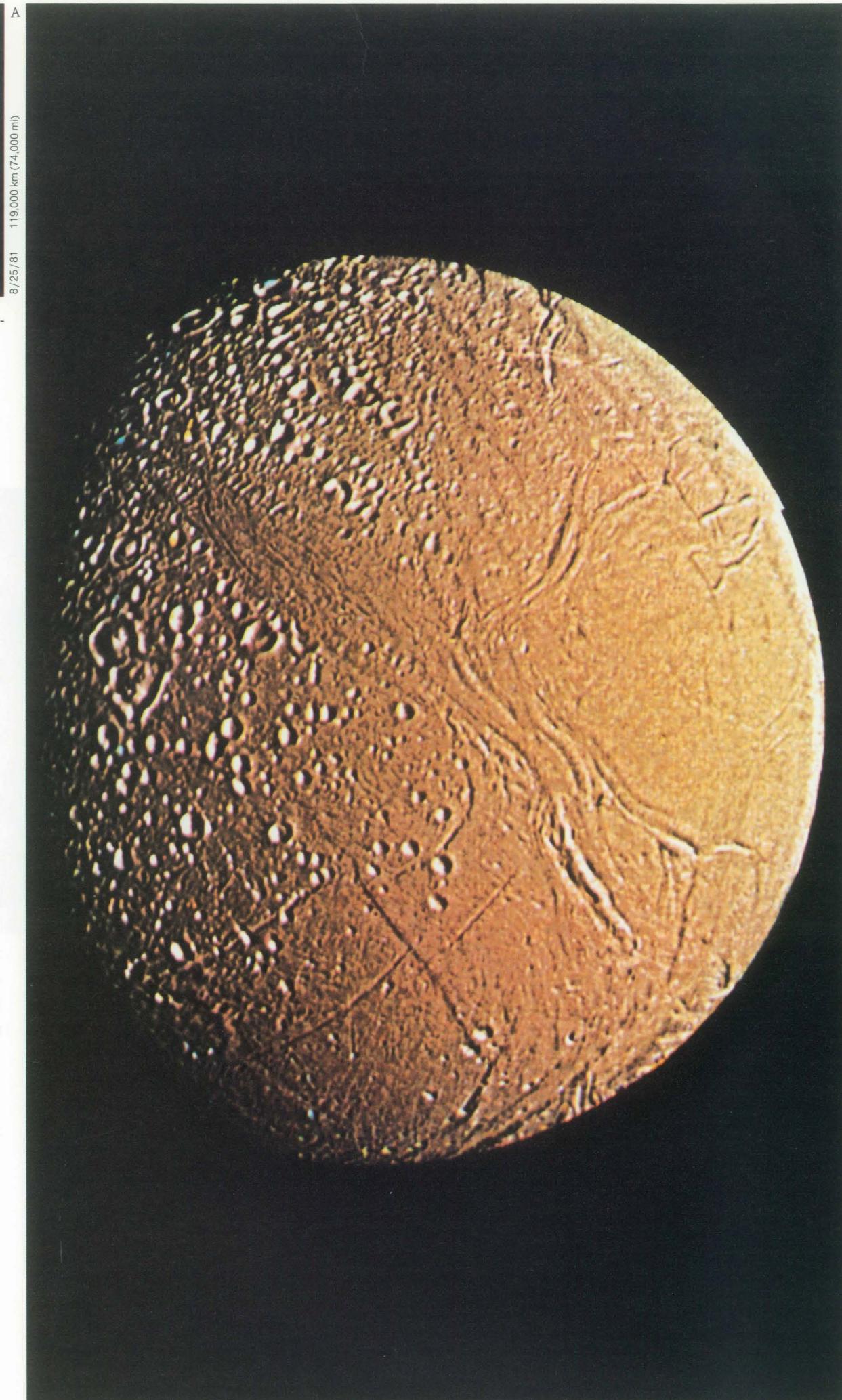
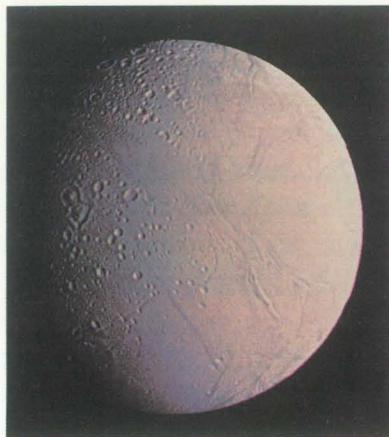


Several small, unnamed Saturnian satellites were captured in a composite family portrait. (E, left to right) 1980S28 [1980 (year), S (Saturn), 28 (sighting)] orbits Saturn just outside the A-ring. It is 40 by 20 kilometers (25 by 12 miles) and helps to confine the A-ring's outer edge. The next pair (top and bottom) are 1980S26 and 1980S27, the F-ring shepherds. They are 110 by 90 by 70 kilometers (68 by 56 by 43 miles), and 140 by 100 by 80 kilometers (87 by 62 by 50 miles), respectively. The top satellite is the outer shepherd. The next pair (top and bottom) are

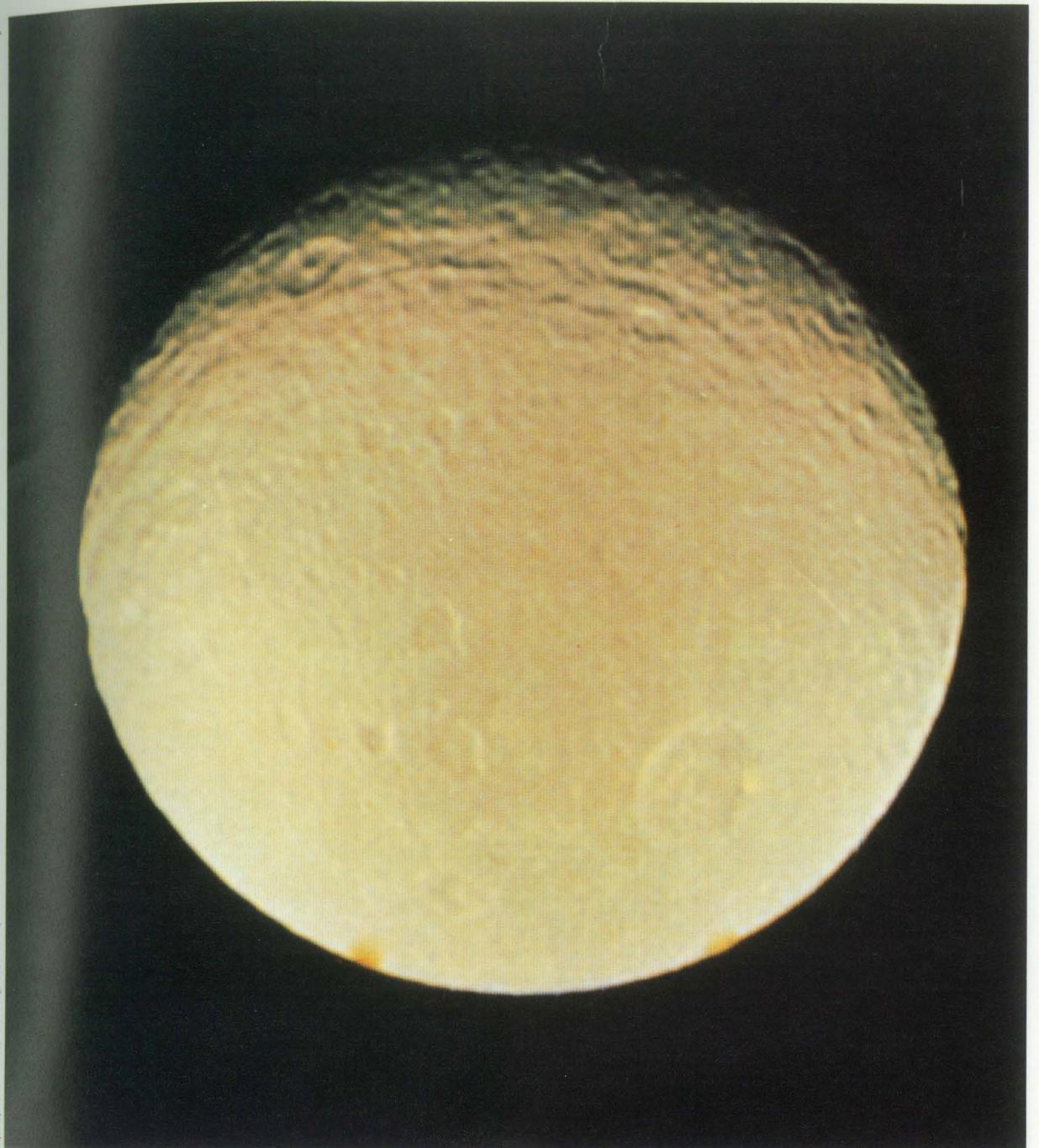
the leading and trailing coorbital satellites, respectively, called 1980S1 and 1980S3. They are (leading) 220 by 200 by 160 kilometers (137 by 124 by 99 miles) and (trailing) 140 by 120 by 100 kilometers (87 by 75 by 62 miles). As the trailing satellite overtakes the leading, they exchange orbits without colliding, circling Saturn in a four-year pattern of musical chairs. The leading

coorbital is the largest of the unnamed satellites. The next pair (top and bottom) are 1980S25 and 1980S13. They are called the Tethys Trojans, since they share Tethys' orbit, about 60 degrees behind and 60 degrees ahead. Similarly, 1980S6 (far right) moves in the same orbit as Dione, about 60 degrees ahead. 1980S6 is 36 by 32 by 30 kilometers (22 by 20 by 19 miles). The Tethys Trojans are only slightly smaller. At least four, and possibly several more,

tiny satellites have been discovered in Voyager pictures since the second encounter, bringing the total to more than 20.

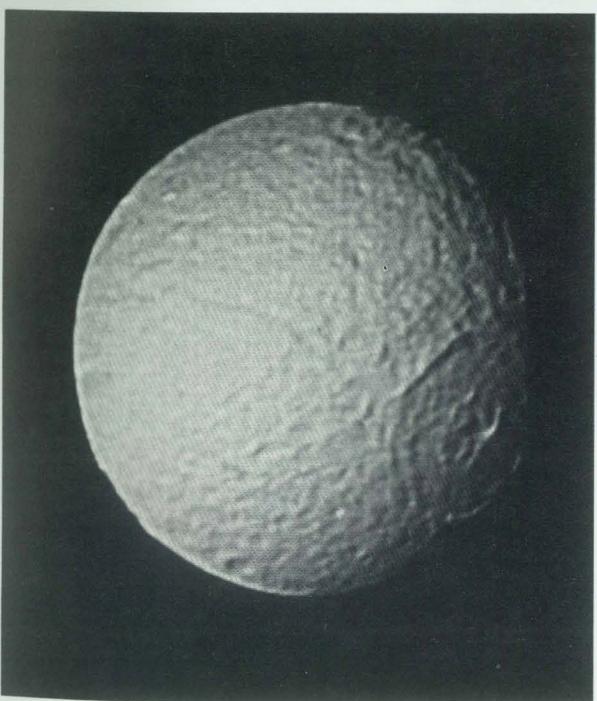


A



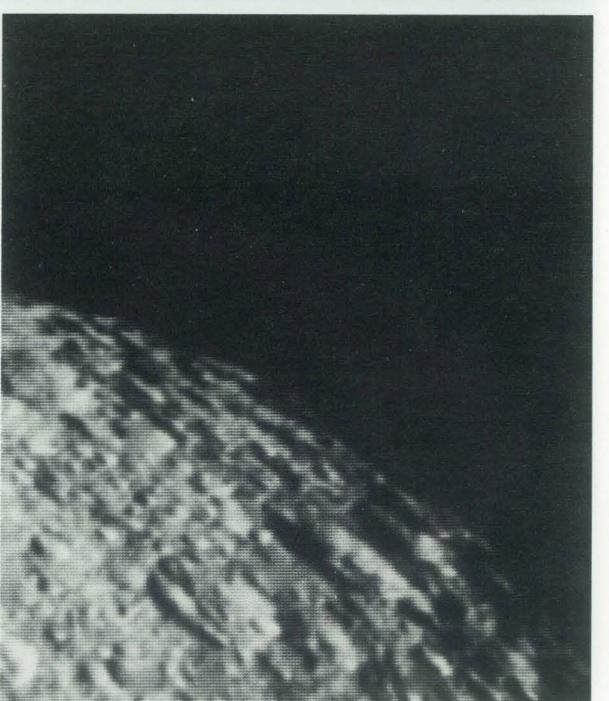
8/25/81 594,000 km (368,000 mi)

B



8/26/81 120,000 km (74,500 mi)

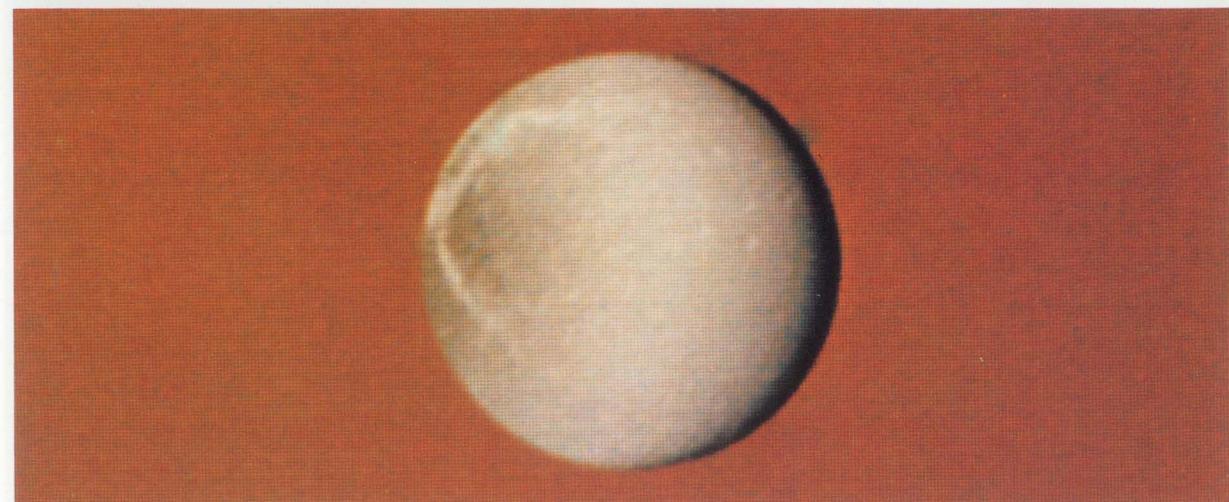
C



8/25/81 826,000 km (513,000 mi)

A huge, globe-girdling canyon and a jumble of impact craters mark Tethys' surface. A portion of the canyon (A), stretching over three-quarters of the circumference, loops from horizon to horizon. The canyon, named Ithaca Chasma, is about 2,500 kilometers (1,550 miles) long, has an average width of about 100 kilometers (62 miles), and a depth of 3 to 5 kilometers (1.8 to 3.1 miles). If Tethys were once a ball of liquid water covered with a thin, solid crust, freezing of the interior would have produced surface expansion comparable to the area of the chasm, but not necessarily as a single, circumferential canyon. A huge crater dominates the photo at lower left (B). It is 400 kilometers (249 miles) in diameter, more than one third Tethys' 1,060-kilometer (660-mile) diameter. Creep or viscous flow in the outer layers of the body has probably allowed the crater to recover almost to the original shape of Tethys' surface. The crater compares with the large one on Mimas. Calculations have shown that, assuming similar thermal gradients and compositions for the outer layers of both satellites, the great crater on Tethys could flatten over geologic time, while that on Mimas could retain its original shape. Relative positions of the crater and Ithaca Chasma suggest a connection. The highest resolution photo of Tethys (C), with two kilometers (1.2 miles) per line pair resolution, shows a region of heavily cratered ancient terrain. In addition, Tethys, like Dione, has one region on its trailing face that is relatively uncratered, probably the result of flooding of the area by material erupting from the interior.

Dione, which like Tethys and Rhea is more than half water ice, is only slightly larger than Tethys but appears to have had a very different geologic history. Dione stands out against Saturn's atmosphere (B) in this photo taken during Voyager's approach. The trailing hemisphere (to left) shows a darkened portion of the surface interlaced with bright streaks. Although there is a suggestion of a crater or basin near the center of the bright markings, the markings do not form the pattern expected for crater rays. They may be fractures associated with faults through which water has come to the surface. The same darkened region is at the right hand limb (A). Some bright streaks appear to have vertical relief, lending credence to the suggestion they are fractures. Substantial differences in crater population density are seen across the surface. Near the center of the picture, adjacent to the terminator, crater density is particularly low, implying regions that are somewhat younger than the more heavily cratered, adjacent areas. Such a plains area could be formed as material rose from the interior, flooding that portion of the surface and covering the older, larger craters. The origin of the complex, branching fractures near the north pole is under debate. A large crater in the upper portion of the photo is about 130 kilometers (81 miles) in diameter. Large craters have pronounced central peaks, formed by rebound of the surface after the initial compression during impact.

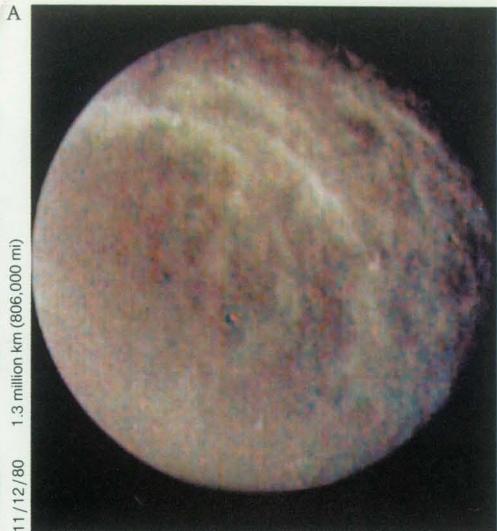


A

11/12/80 162,000 km (100,600 mi)

B

11/11/80 1.2 million km (744,000 mi)

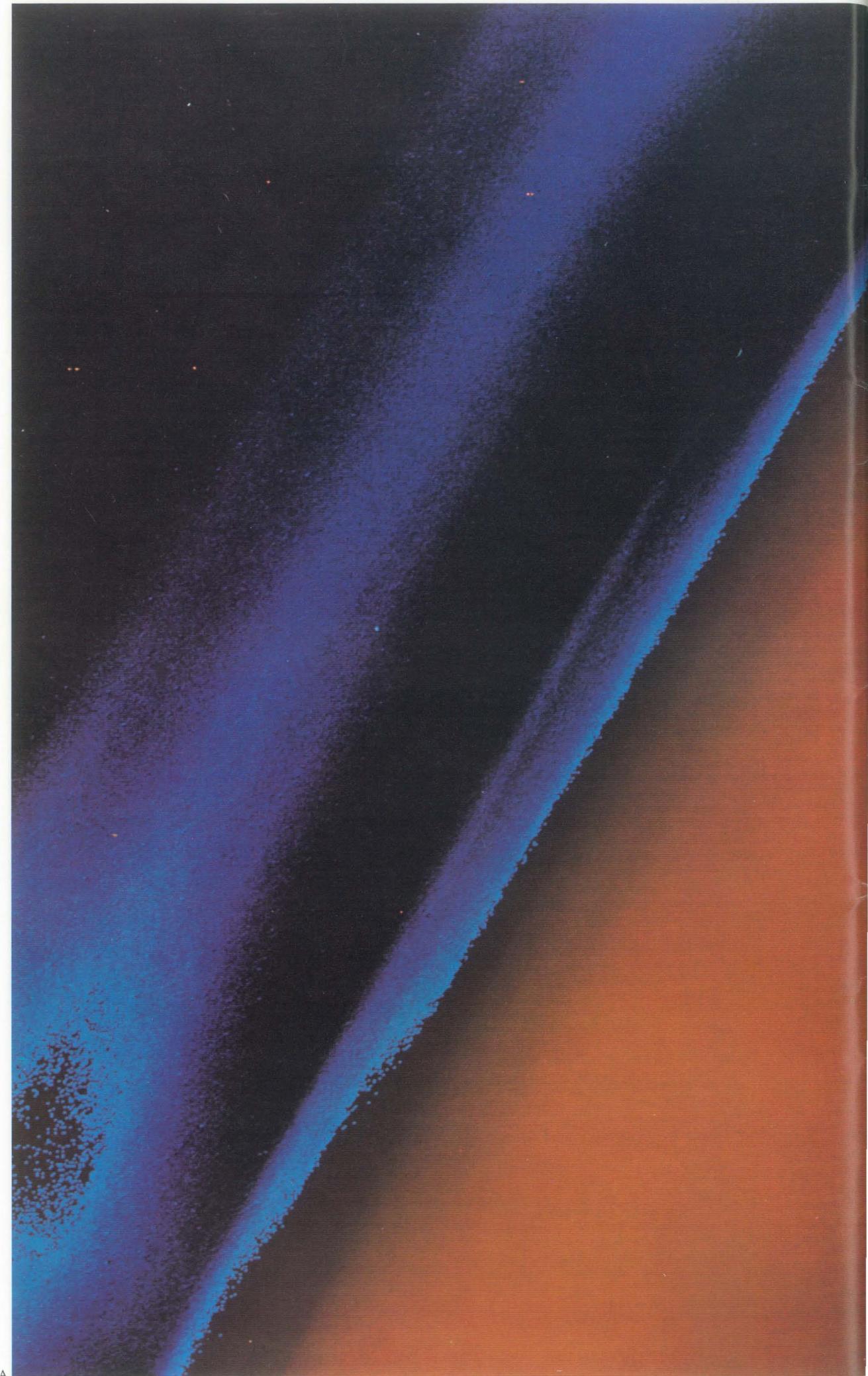


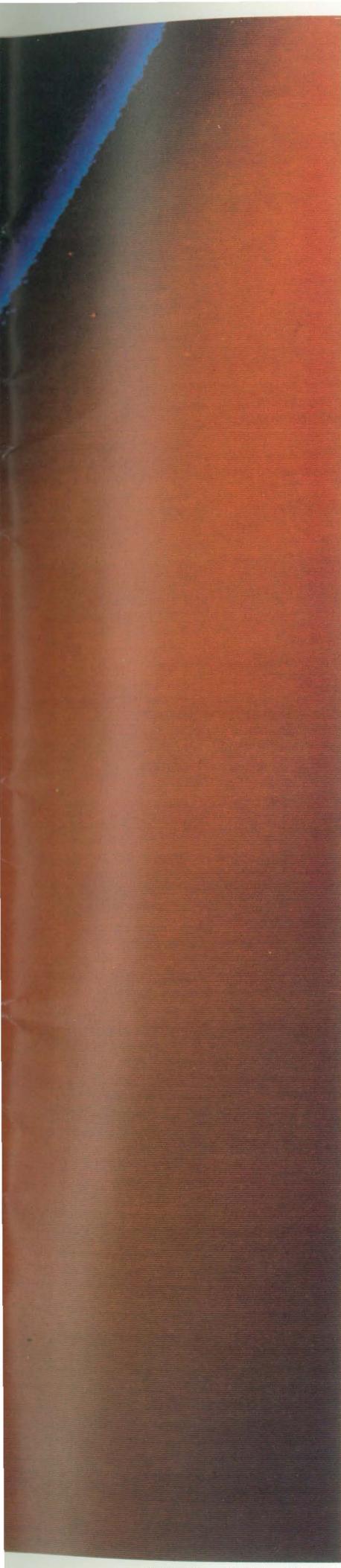
B



Like the majority of Saturn's satellites, Rhea is composed mainly of water ice, and so its surface is reflective and presents an almost uniform white appearance. Of particular interest (A) are the bright streaks crossing Rhea's face. As in the case of Dione, the streaks are believed to be caused by fresh ice that came from beneath the surface. The streaks are in a darkened area of the trailing hemisphere, again like Dione. (B) is of a region near Rhea's equator, on the side that faces Saturn. It shows a very heavily cratered, ancient terrain, indicating a surface dating to the period immediately after formation of the planets 4.6 billion years ago. Many of the larger craters have a polygonal shape, suggesting that a rubble zone makes up the upper crust. White markings on the edges of several craters are probably due to fresh ice deposits, or fresh material exposed on the crater walls. Other regions of Rhea show signs of having been resurfaced later by somewhat darker material, erasing the record of the earliest cratering episode. Those areas are deficient in large craters, indicating that there was a later cratering episode that was lighter than the earlier one.

Titan is the largest satellite in the Saturn system and the only one in the solar system known to have a substantial atmosphere. The main constituent of Titan's atmosphere is nitrogen. The hazes (false-color blue and orange layers in A) are formed from complex organic polymers. They result from the organic photochemistry occurring in Titan's atmosphere—the action of sunlight on methane, which makes up a few percent of the atmosphere. Some of the products of that chemistry include ethane, acetylene, ethylene, methyl acetylene, propane, diacetylene, cyanoacetylene, cyanogen, hydrogen cyanide, and perhaps carbon monoxide. Thus Titan's atmosphere may contain the four elements (carbon, hydrogen, nitrogen, and oxygen) essential to the formation of life. Extremely cold temperatures, however, inhibit formation of the complex organic molecules necessary for living organisms. Nevertheless, the study of Titan's organic chemistry is important because the processes may be similar to those that occurred on Earth before life began. Temperature on Titan's surface is 95°K (-288°F) and drops to a minimum of 72°K (-330°F) at 40 kilometers (25 miles) altitude. As a result, there are probably lakes of liquid methane on the surface and clouds of liquid and frozen methane in the atmosphere. None of this can be seen, however, because the orange-colored haze, about 250 kilometers (155 miles) above the surface, completely hides it. Several additional haze layers can be seen standing above Titan's limb.

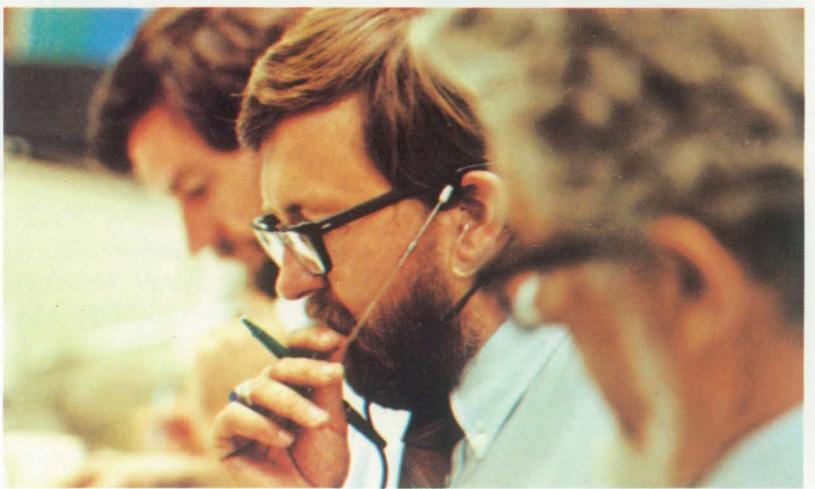
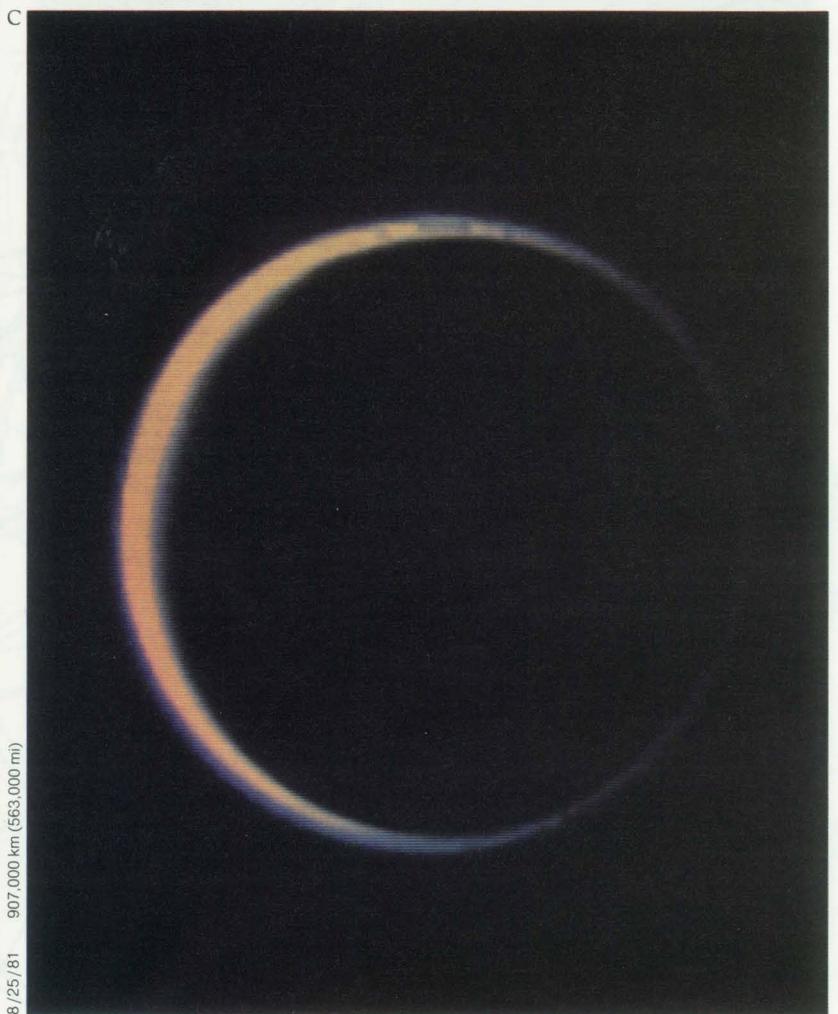




B



C



11/12/80

22,000 km (14,000 mi)

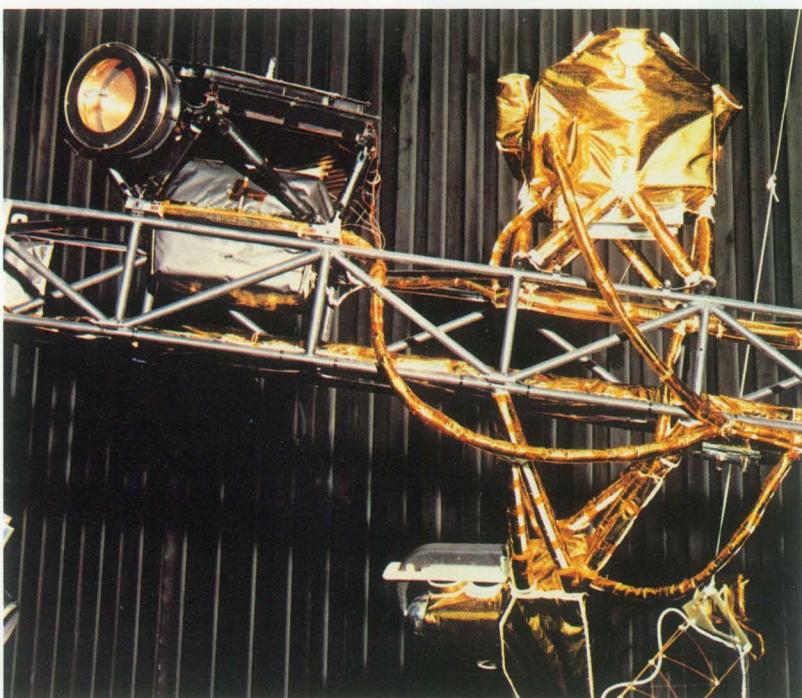
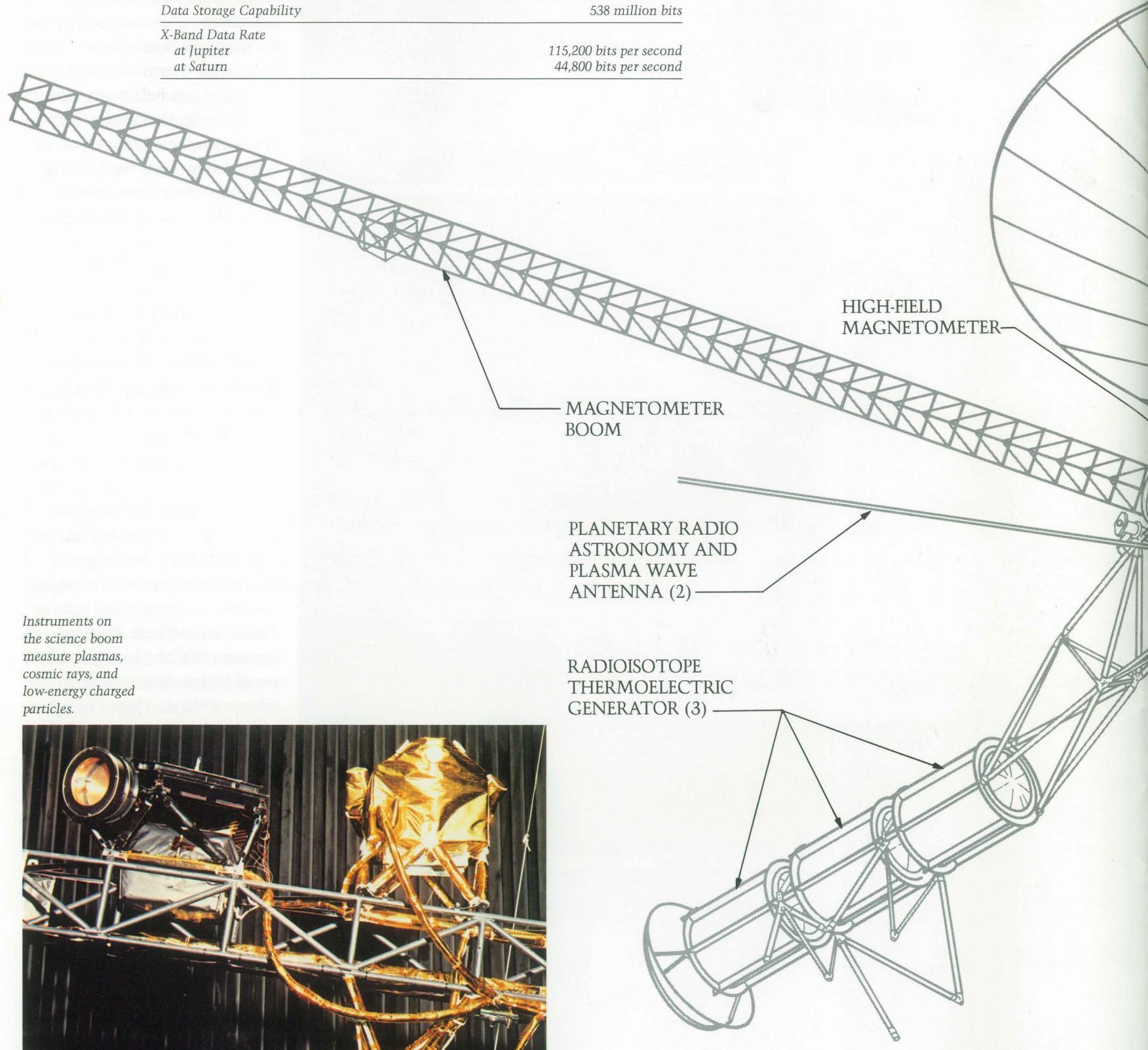
Titan's atmosphere has a surface pressure 60 percent greater than Earth's surface pressure. Voyager observed several features in the atmosphere. A dark ring (B) at about 70 degrees north latitude may be a seasonal effect, as may be the brighter appearance of the atmosphere in the southern hemisphere. Seasons on Titan last about seven and one-half years, and it was spring in the north when the Voyagers arrived. Also apparent is the fainter haze layer due to smaller particles that stands above the main, orange haze layer. Colors of Titan were exaggerated in this photo (C) taken by Voyager 2 as it looked at Titan's dark side. The atmosphere is visible over the entire circumference, showing that the haze layers extend hundreds of kilometers above the opaque orange haze layer. Light scattering by submicron-size particles accounts for the blue appearance of upper layers of haze. No simple model of particle sizes and shapes in the haze accounts for the brightness and polarization of light by Titan's atmosphere. It seems apparent that the haze particles are of varied sizes or of nonspherical shape. Titan's diameter is 5,150 kilometers (3,200 miles).

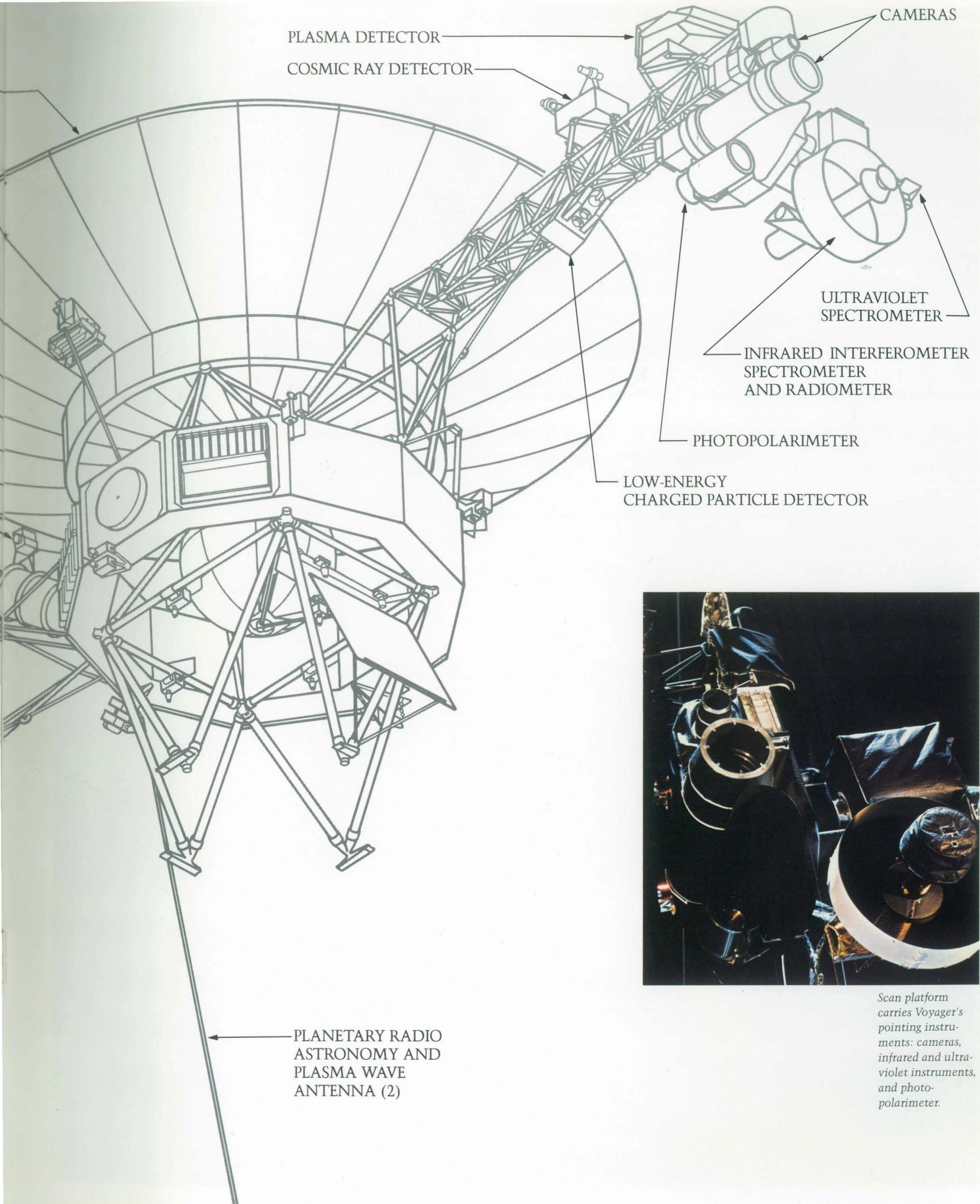
THE VOYAGER SPACECRAFT

SPACECRAFT FEATURES

Spacecraft Mass	824 kg (1,817 lb)
Science Instruments Mass	106 kg (234 lb)
High-Gain Antenna Diameter	3.7 m (12 ft)
Radioisotope Thermolectric Generator (RTG) Power (at Saturn)	~430 W
Data Storage Capability	538 million bits
X-Band Data Rate at Jupiter	115,200 bits per second
at Saturn	44,800 bits per second

HIGH-GAIN ANTENNA
(3.7-meter diameter)





Scan platform carries Voyager's pointing instruments: cameras, infrared and ultraviolet instruments, and photopolarimeter.

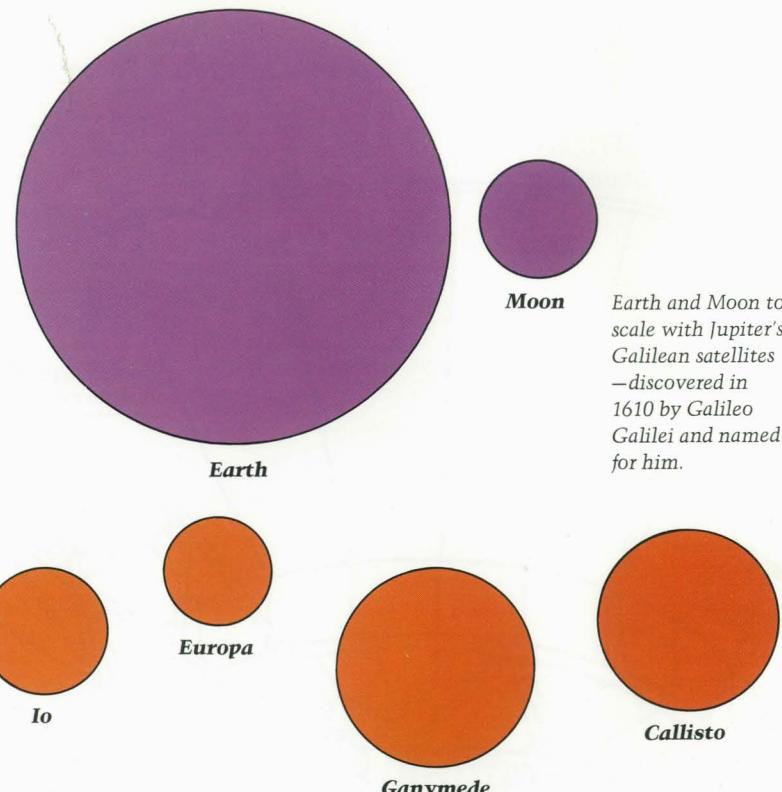
JUPITER: SCIENCE HIGHLIGHTS

- ★ The two Voyagers took almost 33,000 photos of Jupiter and its satellites.
- ★ Features of broadly different sizes in Jupiter's atmosphere move with uniform velocities, indicating that mass motion and not wave motion was being observed.
- ★ Material associated with the Great Red Spot moves in a counterclockwise direction. The rotation period at the outer edge is about six days; little motion was observed at the center.
- ★ Cloud-top lightning bolts, similar to superbolts on Earth, were observed.
- ★ Auroras similar to Earth's northern lights were observed in both ultraviolet and visible light.
- ★ Whistler emissions were detected in the Jovian atmosphere. They were interpreted as lightning whistlers.
- ★ Jupiter has a ring system. Its outer edge is 128,000 kilometers (80,000 miles) from the center of the planet. The ring is no more than 30 kilometers (20 miles) thick.
- ★ Photos showed at least eight volcanoes erupting on the Galilean satellite Io.
- ★ A torus of sulfur, oxygen, and sodium surrounds Jupiter at the distance of Io. The satellite appears to be the source of the material.
- ★ An electric current of about 3 million amperes was detected in the flux tube connecting Io and Jupiter; it is three times stronger than predicted.
- ★ Europa displayed a large number of intersecting linear

markings on its surface. They show no topographic relief.

★ Ganymede showed two distinctly different kinds of terrain—cratered and grooved. Its ice-rich crust appears to have been under tension from global tectonic processes. Ganymede is the largest satellite in the solar system, with a radius of 2,638 kilometers (1,640 miles).

★ Callisto has an ancient, heavily cratered crust with remnant rings of enormous impact basins.



Earth and Moon to scale with Jupiter's Galilean satellites—discovered in 1610 by Galileo Galilei and named for him.

"All men by nature desire knowledge."

ARISTOTLE



Jupiter and the four Galilean satellites, Io, Europa, Ganymede and Callisto. Montage was constructed from five Voyager photos.



SATURN: SCIENCE HIGHLIGHTS

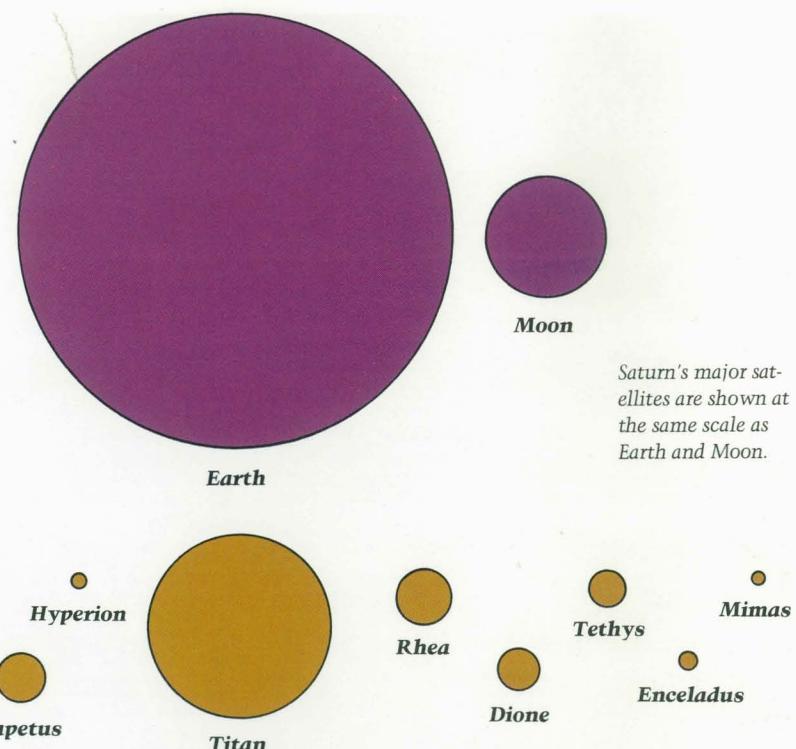
- ★ The Voyagers took more than 30,000 photos of the Saturn system.
- ★ There is less helium in the top of Saturn's atmosphere than in Jupiter's.
- ★ Subdued contrasts and color differences are primarily a result of either more horizontal mixing or less production of localized colors on Saturn than on Jupiter.
- ★ Winds blow at extremely high speeds on Saturn. Near the equator, the Voyagers measured winds of about 500 meters per second (1,100 miles an hour). The winds blow primarily in an eastward direction.
- ★ The Voyagers found aurora-like ultraviolet emissions at mid-latitudes on Saturn, and auroras at higher latitudes.
- ★ The Voyagers discovered radio emissions from the planet with which they determined the length of Saturn's day—10 hours, 39 minutes, 24 seconds.
- ★ The complicated structure in Saturn's rings appears to be caused, at least in part, by density waves, created by gravitational interactions with several of the inner satellites. Few clear gaps exist anywhere in the rings.
- ★ Radial, spoke-like features were discovered in the rings and are still not well understood.
- ★ Titan, Saturn's largest satellite, has an atmosphere composed of nitrogen, methane, and several organic compounds, including hydrogen cyanide.
- ★ Titan's surface atmospheric pressure is 1.6 bars, 60 percent greater than the surface pressure of Earth.

★ The temperature at the surface of Titan is 95°K (−288°F). Methane, therefore, possibly plays much the same role on Titan as water does on Earth.

★ Saturn's regular satellites appear to be composed primarily of ice. Phoebe, the outermost, is believed to be a captured asteroid.

★ Many new satellites have been discovered at Saturn, some from Earth-based observations, others by the two Voyagers. More than 20 are known. Scientists expect to find more.

★ The size of Saturn's magnetosphere, like Jupiter's, is controlled by external pressure of the solar wind.

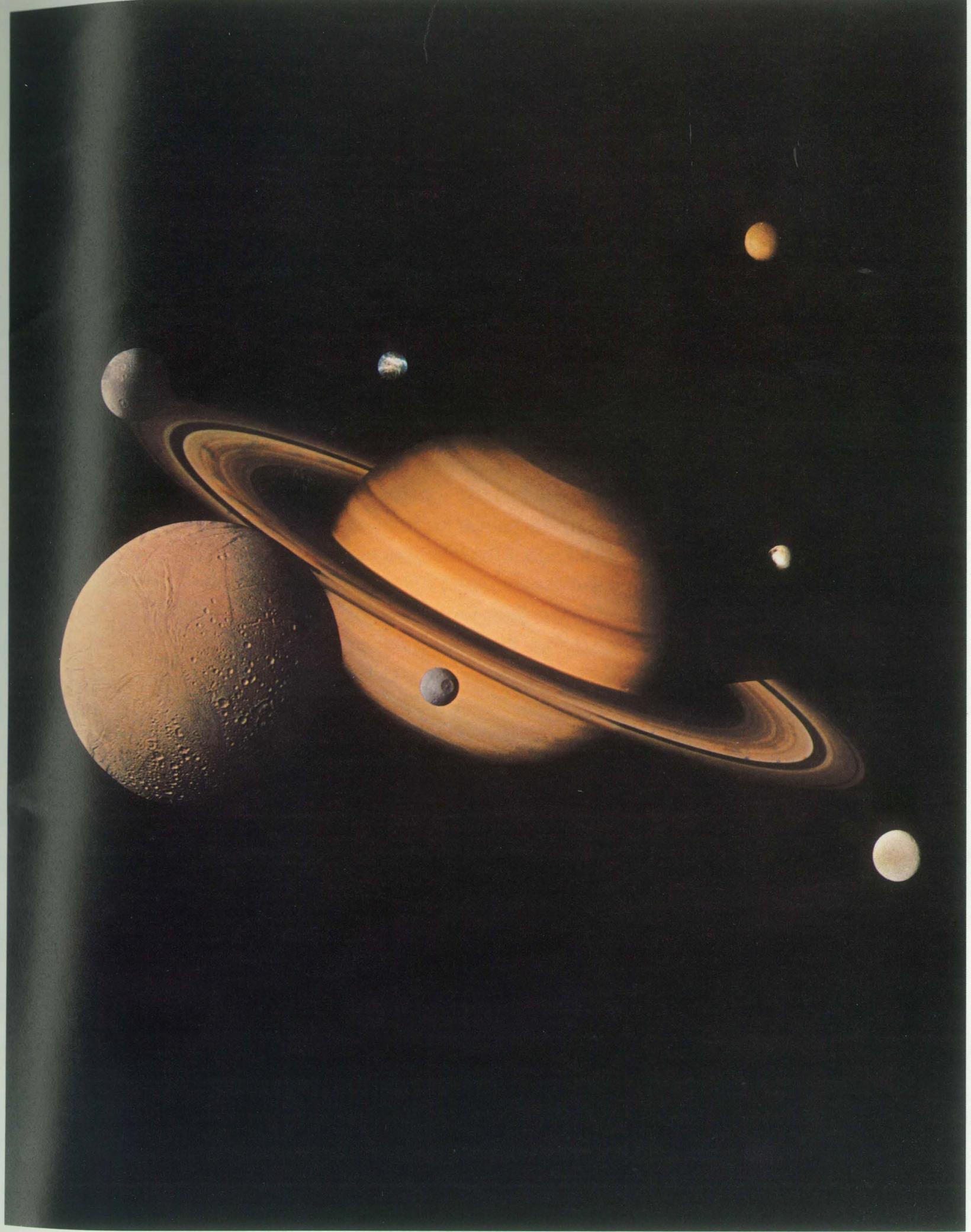


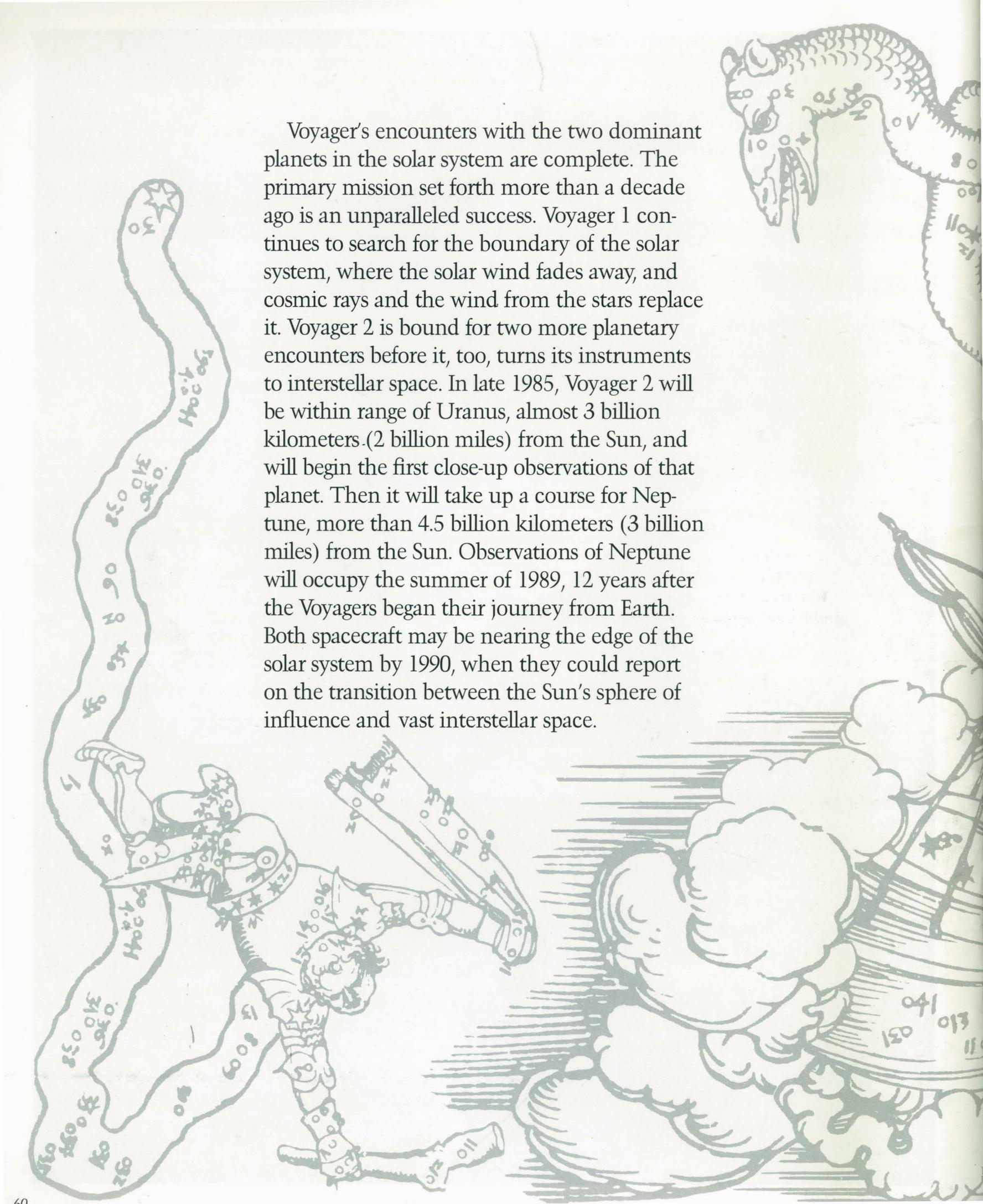
"Science increases our power in proportion as it lowers our pride."

CLAUDE BERNARD

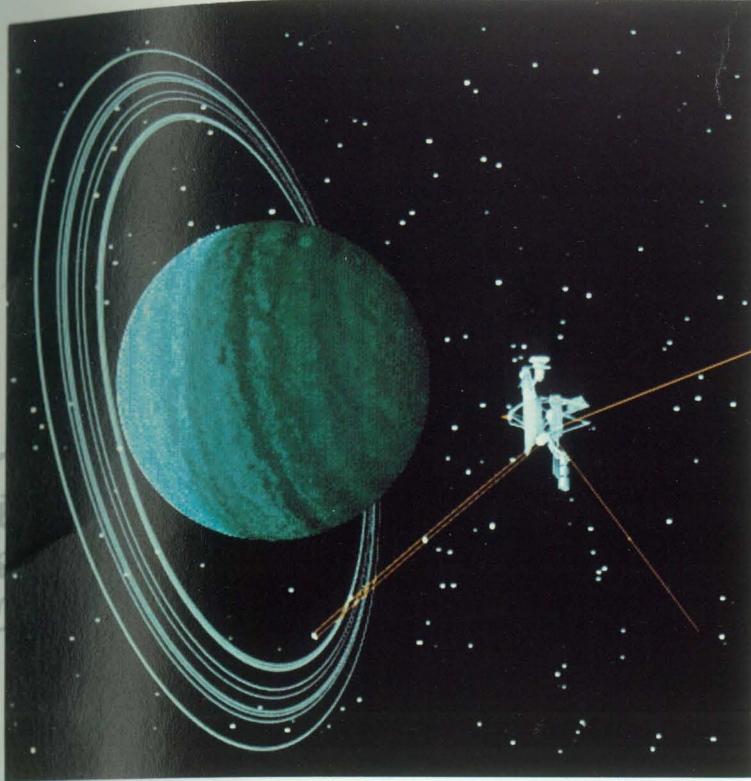


Saturn and its major satellites: a montage of Voyager pictures. Satellites are (clockwise from upper right) Titan, Iapetus, Tethys, Mimas, Enceladus, Dione, and Rhea.

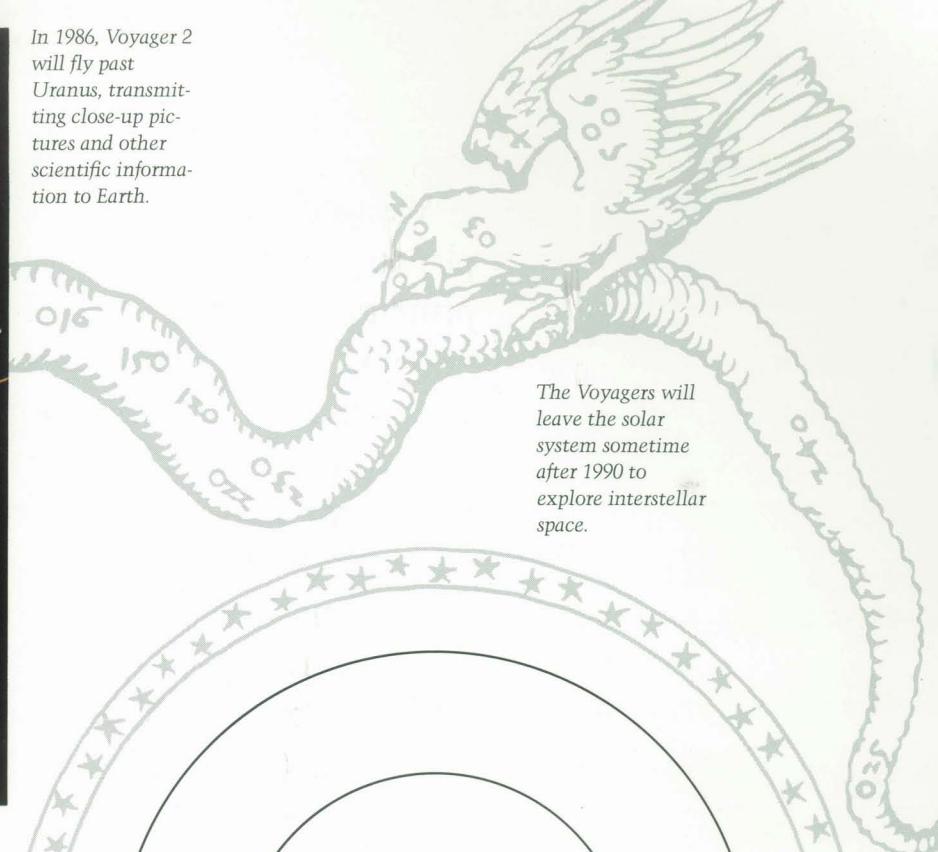




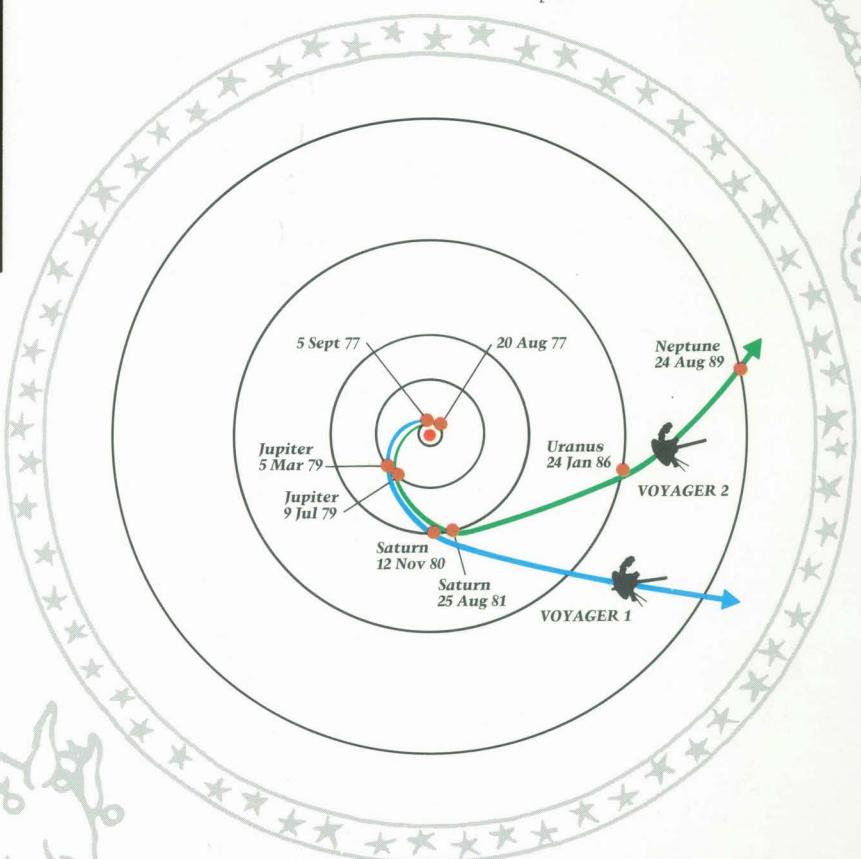
Voyager's encounters with the two dominant planets in the solar system are complete. The primary mission set forth more than a decade ago is an unparalleled success. Voyager 1 continues to search for the boundary of the solar system, where the solar wind fades away, and cosmic rays and the wind from the stars replace it. Voyager 2 is bound for two more planetary encounters before it, too, turns its instruments to interstellar space. In late 1985, Voyager 2 will be within range of Uranus, almost 3 billion kilometers (2 billion miles) from the Sun, and will begin the first close-up observations of that planet. Then it will take up a course for Neptune, more than 4.5 billion kilometers (3 billion miles) from the Sun. Observations of Neptune will occupy the summer of 1989, 12 years after the Voyagers began their journey from Earth. Both spacecraft may be nearing the edge of the solar system by 1990, when they could report on the transition between the Sun's sphere of influence and vast interstellar space.



In 1986, Voyager 2 will fly past Uranus, transmitting close-up pictures and other scientific information to Earth.

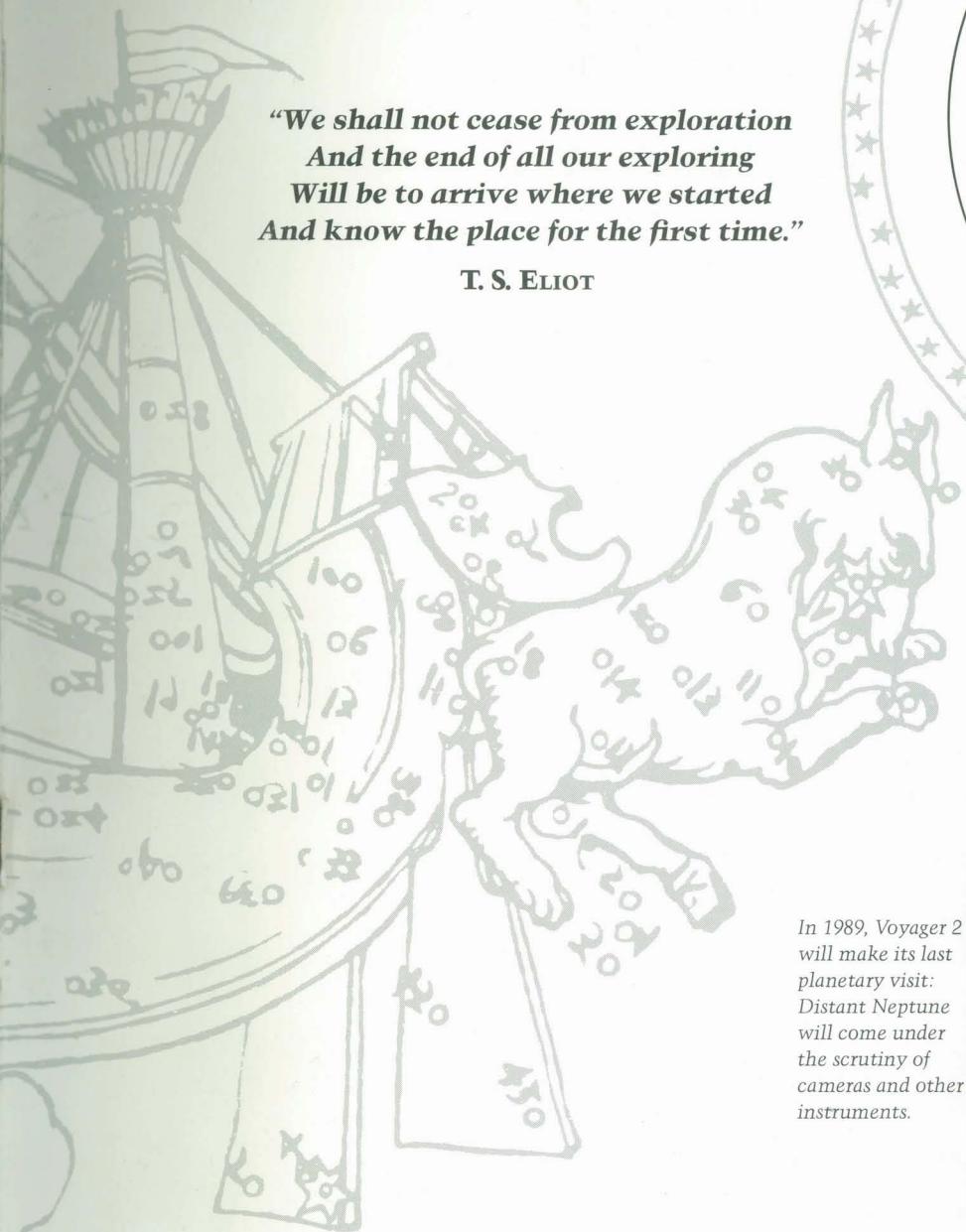


The Voyagers will leave the solar system sometime after 1990 to explore interstellar space.

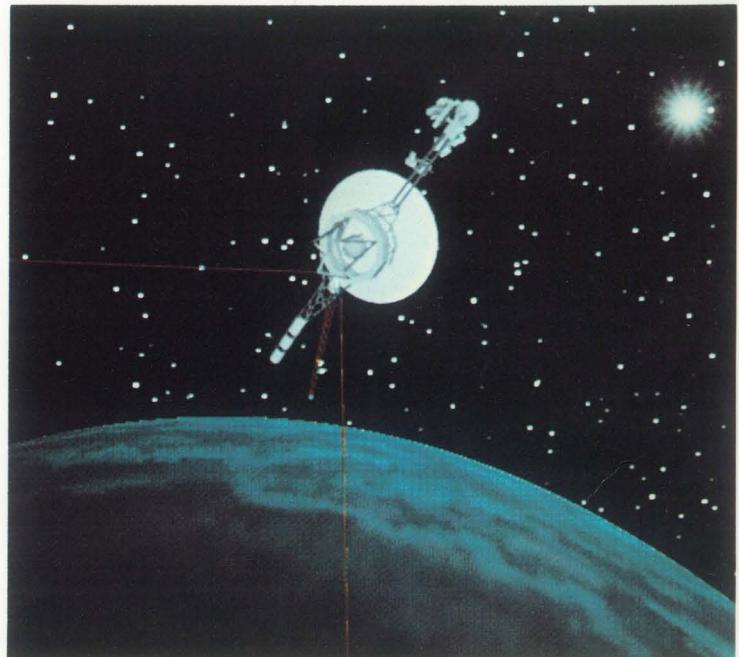


*"We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time."*

T. S. ELIOT



In 1989, Voyager 2 will make its last planetary visit: Distant Neptune will come under the scrutiny of cameras and other instruments.



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